Coast Eng. Res. Ctr.

MR 76-11

Measurement Techniques for Coastal Waves and Currents

by
P.G. Teleki
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MISCELLANEOUS REPORT NO. 76-11
NOVEMBER 1976

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: MR 76-11	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE *(and Subtitle)*: MEASUREMENT TECHNIQUES FOR COASTAL WAVES AND CURRENTS	5. TYPE OF REPORT & PERIOD COVERED: Miscellaneous Report
6. PERFORMING ORG. REPORT NUMBER	
7. AUTHOR(s): P.G. Teleki, F.R. Musialowski, D.A. Prins	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Department of the Army, Coastal Engineering Research Center (CEREN-GE), Kingman Building, Fort Belvoir, Va. 22060	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: D31191
11. CONTROLLING OFFICE NAME AND ADDRESS: Department of the Army, Coastal Engineering Research Center, Kingman Building, Fort Belvoir, Va. 22060	12. REPORT DATE: November 1976
	13. NUMBER OF PAGES: 75
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*	15. SECURITY CLASS. *(of this report)*: UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Current meters	Telemetry
Dye tracers	Towed Oceanographic Data Acquisition System
Nearshore currents	Wave gages
Sea sled	Waves

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

A Towed Oceanographic Data Aquisition System (TODAS) consisting of a towed platform (sea sled) with current meters and a wave gage has been developed for collection of information on nearshore currents and waves. Data acquired by the sensors are telemetered to shore and digitally recorded. TODAS is used for real-time evaluation of flow characteristics between shore and a depth of 9.14 meters (30 feet); this mobile battery-operated system can be used at remote locations. The system has been used principally in two experimental designs: (a) Monitoring the distribution of longshore currents in shore-normal profiles, and

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(b) a combination of Eulerian-Lagrangian experiments where fixed-point metering is supported by aerial photography of diffusing dye plumes and concentration measurements of the dye tracers.

PREFACE

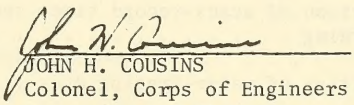
This report is published to provide an analysis and discussion of the Towed Oceanographic Data Aquisition System (TODAS), developed for the collection of information on nearshore currents and waves. The work was carried out under the coastal processes research program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by Dr. P.G. Teleki, F.R. Musialowski, and D.A. Prins under the supervision of Dr. David B. Duane, former Chief, Geological Engineering Branch, and Dr. William R. James, his successor.

Several people were instrumental in designing and constructing parts of the TODAS: E.A. Maiolatesi, N.F. Lang, and B.W. Keebaugh of the Instrumentation Branch, who designed the circuitry of the wave gage and current meters; Dr. J.R. Weggel, L.L. Watkins, and C.D. Puglia, who helped with the design and modification of the sea sled; and G. Sine and other members of the Hydrographic Survey Section, Survey Branch, U.S. Army Engineer District, Los Angeles, whose enthusiastic participation in the field experiments was much appreciated. The support and ideas of Dr. Duane on the sea sled and experimentation are gratefully acknowledged.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.



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Colonel, Corps of Engineers
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CONTENTS

		Page
I.	INTRODUCTION	7
	1. General Concepts	7
	2. Background and Objectives	9
II.	TOWED OCEANOGRAPHIC DATA ACQUISITION SYSTEM (TODAS)	11
	1. Sea Sled	11
	2. Instrumentation	22
III.	POWER REQUIREMENTS	30
	1. Electronics	30
	2. System Calibration	41
IV.	EXPERIMENTAL DESIGNS	46
	1. Continuous Surveys Along Shore-Normal Profiles	46
	2. Fixed-Point Measurements	56
	3. Fixed-Point Measurements Combined with Lagrangian Techniques	56
	4. Aerial Photography	61
V.	CONCLUSIONS AND RECOMMENDATIONS	68
	LITERATURE CITED	69
	APPENDIX	71

TABLES

1	Scan rate selections	39
2	Timed start intervals	36
3	Comparison of scans-record times records-file versus time of recording	42
4	Properties of water-tracing dyes	62

FIGURES

1	Sea sled	10
2	R_e versus z/d versus C_D	13
3	Distribution of $\frac{U_{max}}{(H/T)}$, du/dt, case 5-B	14
4	Distribution of U_{max}, du/dt, case 3-D	15
5	Case 5-B, f_D and f_i versus phase angle	16

FIGURES

		Page
6	Case 3-D, f_D and f_i versus phase angle.	17
7	Engineering drawing of sea sled	20
8	Reference axes for sensor alinement	23
9	B-10 current meter with schematic	25
10	Diagram reed switches and closure sequence.	26
11	B-7 sensor.	27
12	Response curve, B-10 sensor	28
13	Photos of wave gage	29
14	Batteries, charger, and cylinder for power package	31
15	Bulkhead connectors	32
16	Generalized schematic of onboard electronics.	33
17	Instrument package and cylinder	34
18	Transmitter	34
19	Onshore electronics	35
20	Flow diagram, instrument components	37
21	Data logger with enlargement of control and monitoring panel.	38
22	Magnetic tape recorder and specifications	40
23	B-7 sensor, V_{max} versus A_{max}.	44
24	B-7 sensor, V_{max} versus A_{min}.	45
25	Phase lag versus frequency.	27
26	True cosine response curve and actual B-10 sensor response.	48
27	Field testing of current meters	49
28	Experimental grid for sea sled experiments.	51

FIGURES

		Page
29	Orthogonally mounted current meters	53
30	Pairs of horizontally mounted current meters	53
31	Example of longshore current distribution	54
32	Example of energy spectra along shore-normal profile	55
33	Current meters alined for measurement in vertical profile	57
34	Comparison of velocities from dye transport and current meters	60
35	Buoy shore-marker grid	63
36	Typical flight lines for imaging coastal dye dispersion	65
37	Zoom Transfer Scope	66
38	Oblique photo of dispersing dye and map of rectified photo	67

MEASUREMENT TECHNIQUES FOR COASTAL WAVES AND CURRENTS

by

P.G. Teleki, F.R. Musialowski, and *D.A. Prins*

I. INTRODUCTION

1. General Concepts.

The coastal zone is the most frequently observed part of the ocean. Its shorelines have been explored and described for at least two centuries, but only in the last 20 years have coastal resources been studied or damages to property systematically documented; however, considerable knowledge about some of its most important physical processes remains to be secured.

This report examines a manner in which coastal currents, one of the least understood processes, may be studied. Currents represent the flow of water which transport and disseminate heat, salt, and particulate matter. Currents converge near headlands and marine structures, diverge near islands and in bays, and influence navigation. Because they are the main transportive mechanism for the sediments on the ocean floor, currents in coastal areas often interfere with human intentions by eroding and depositing sand in undesired locations and in undesired quantities. Probably half of all problems in coastal engineering can directly be traced to this physical process.

The study of currents requires recognition that the flow of water in relatively shallow water may originate in one or more of the following: Wind, waves, tides, density stratification, and even internal waves. The most difficult part of analyzing current records is perhaps in assigning the proper weight to each of the components in a field of complex or interactive flow; also difficult is the assessment of temporal and spatial variabilities (or stabilities) or the modeling of the currents for predictive purposes.

Coastal currents characteristically exhibit the effect of seasonal changes and trends which may be peculiar to a geographic area of study, and incorporate components of the large-scale circulation of the oceans. Experiments which include consideration of long-term changes in current velocities, distribution, and structure are not commonly planned for the coastal zone.

Engineering practice often classifies coastal currents by direction (onshore versus alongshore) and by area shoreward or seaward of the zone of breaking waves. Coastal engineers prefer to emphasize the longshore currents generated by breaking waves, a natural consequence of its relation to littoral drift; oceanographers tend to view coastal currents in a slowly varying, wind- and pressure-driven, stratified, and bathymetry-dependent sense. In either case, currents represent a sediment-moving

force responsible for sediment entrainment, transport, and deposition, whether occurring in open shelves or in entrances to harbors and tidal inlets. Recent evidence suggests that sediment transport is not limited to the narrow zone between the breaking waves and the limit of their uprush, but that currents of various origin actively transport sediments parallel to shore as distantly as the edge of the Continental Shelf. This sediment transport has implications in offshore engineering, an area of increasing concern.

In nearshore areas, the main contributing factor to current generation is the waves shoaling over the Continental Shelf and refracting with decreasing depth. Depending on the angle of incidence between the wave orthogonal and the bottom contours (ultimately the shoreline), coastal currents might be generated parallel or normal to shore, a matter of considerable engineering significance. The currents contain an admixture of periodic and aperiodic water motions. However, in several geographic areas superimposed wave trains of different amplitudes, frequencies, and directions will combine to produce random wave fields. The flow generated by these waves may be stochastic or ergodic (or neither). During the passage of storms, the wave field and the resulting flow field may also become nonstationary.

The laminar nature of the flow to this point was implicitly assumed, and for the potential flow region of relatively deep waters, this assumption may often be correct. However, at the sea floor the boundary layer may be intermittently to fully turbulent independently of the nature of flow above it. As the water depth decreases shoreward the scales of motion become compressed from three into two dimensions and the result is that coastal, shallow-water currents become increasingly more turbulent for the full depths of flow. This action induces mixing which is characteristically at maximum near breaking waves and by its rotational nature drastically modifies the current-induced motion of sediments. Other effects, such as wave-wave interaction and wave-current interactions, also influence forces imparted to the flow and the sediments. When experiments are designed for the measurement of currents, essentially two techniques are available: the Eulerian method and the Lagrangian method. With the Eulerian method, water motion is observed past one or more fixed points; with the Lagrangian method, a water particle is followed downstream, and changes in its motion (speed and direction) are observed. Neumann (1968) stated, "The most complete description of oceanic currents is obtained from a combination of both Eulerian and Lagrangian methods." This statement is equally appropriate to shallow-water currents whose variations in space and time near the coast, are even more complex than those of major ocean currents.

This study describes Eulerian and Lagrangian techniques used in the measurement of coastal currents. Through technological improvements for the survey of the nearshore flow characteristics, new experimental rationale were developed. The report also documents data collection methods and discusses problems attendant to obtaining accurate measurements.

2. Background and Objectives.

Research in the harsh physical environment of the nearshore zone has always been difficult to implement. The problem area is the zone of breaking waves where navigation and the placement and operation of instruments have had many failures. This zone is of interest to those involved in the study of nearshore sediment transport mechanics, the distribution of longshore currents, and the dispersal and mixing of water masses, the physical description of which has suffered for the lack of continuity in surveys between the beach and the offshore area. Since the wave climate is seldom constant, these surveys must be rapidly conducted, the sensors used must be rugged enough to withstand the wave impact forces, and the environmental parameters measured should be analyzed in real time to collect representative data.

The first requirement is for a device which will negotiate the surf and carry oceanographic instruments at the same time. Several precedents for such an implement exist, and most result from the interest in military amphibious operations during World War II, although the type developed by Isaacs (1945) was intended to carry demolition charges. Isaacs' sled was perhaps the first of a generation of similar devices designed explicitly to negotiate the surf. Another who experimented with self-propelled (or wave-action propelled) sleds was Johnson (1949) in measuring water depth.

The sled described in this report (Fig. 1) was originally designed by Robert Sears of the U.S. Army Engineer District, Baltimore. Kolessar and Reynolds (1966) named it the *Sears sled*. It was engineered to be a towed stadia rod (a mast riding on a frame) for sounding the nearshore zone. The sled could be winched to shore from 9.14 meters (30 feet) of water or less but had to be deployed again at the beginning of the next survey line; Kolessar and Reynolds engaged a helicopter for this phase of the work.

Certain aspects of the Coastal Engineering Research Center (CERC) *sea sled* (using Johnson's (1949) terminology), such as the sled's framework and onshore incremental movement in one mode of operation, reflect its heritage. However, the use of the sled in the measurement of nearshore currents and waves is a departure from previous experience. The sled is a component in TODAS (Towed Oceanographic Data Acquisition System), which includes the amphibious craft towing the sled, the sensors and the associated telemetry, data conversion and storage units, future improvements (cathode ray tube (CRT) minicomputer), auxiliary dye studies, and aerial photography. At present the capabilities of TODAS extend to measuring currents and waves in shallow water (in 0.91 meter (3 feet) < depth < 9.14 meters (30 feet)) in "quasi-real time," with provisions made for increased capabilities (more and varied-purpose instrumentation and on-site data analysis).

The development of TODAS was a 3-year effort, during which the system was continually upgraded and tested under both laboratory and field con-

Figure 1. Sea sled.

ditions. Between 1972 and 1974 several experiments were held in California and one in Michigan. These experiments included navigation tests, instrument calibration, different data collection modes, evaluation of experimental designs, and timing of support operations (or the support of other experiments).

The goal of all field experiments was to collect the most comprehensive environmental data possible with the given capabilities. Thus, many support operations required collection of wind, temperature, and salinity data, the areal reconnaissance of bottom roughness, and sediment properties. TODAS was used on several occasions to support radioactive sediment tracing (RIST). Most operations were conducted near coastal engineering structures so that the results could provide insight to their performance.

TODAS is unique in that it is self-contained, i.e., requiring no field installations or commercial power sources, and therefore can be used at remote sites. It is applicable to both coastal and estuarine research.

II. TOWED OCEANOGRAPHIC DATA ACQUISITION SYSTEM (TODAS)

The separable and identifiable components of TODAS are: (a) The sea sled; (b) the current meters; (c) the wave gage, onboard electronics, and power supply; (d) the telemetry; (e) the onshore signal conversion; and (f) the data conversion and recording units. Certain other components attached by experimental design, such as the multispectral photographic equipment used in imaging tracer dyes for charting surface currents, may also be included.

1. The Sea Sled.

The functional parts of the sled are a 9.14-meter-long mast, attached crossmembers (spars) supporting current meters, a frame, and a pair of skis on which the mast-spar assembly and two cylinders containing an electronic package and the power supply ride. The total weight of the sea-sled frame and the components of the data acquisition system mounted on the sled is 347 kilograms (765 pounds), exclusive of additional weights which can be added for more stability in a high-energy surf. Although the sea sled has a low gravitational center, certain conditions can overturn the platform, e.g., excessive wave forces, steep slopes, or a combination of both.

A calculation of the critical overturning moment and a description of the upper (safe) limit of environmental conditions under which the sled may be used in the field are given below.

a. Wave-Force Analysis. In the operation of a structure at sea, two commonly encountered hazards are structural damage (i.e., bending, breaking, and twisting of members) and overturning of an unanchored platform. Both hazards are the result of excess wave forces. Thus, the design of a structure requires a survey of wave and bottom conditions likely to be

encountered by the towed sea sled and the subsequent calculation of wave forces on the components of the platform.

The total force exerted by waves on a unit section, dz, of an object is composed of the drag force and the virtual mass force:

$$d_f = (f_D + f_i)\, dz \quad , \tag{1}$$

where the drag force is proportional to the square of the orbital velocity in the horizontal plane:

$$f_D = 1/2\ C_D \rho D\ (|u|u) \quad , \tag{2}$$

and the virtual mass force is proportional to the horizontal acceleration force exerted on a mass of water displaced by the object:

$$f_i = 1/4\ C_M \rho \pi D^2\ \frac{\partial u}{\partial t} \quad . \tag{3}$$

In equations (2) and (3), D is the diameter of the cylindrical object, ρ is the mass density of seawater, u is the horizontal component of the orbital wave velocity, and C_D and C_M are the coefficients of drag and inertia, respectively.

The horizontal components of velocity and acceleration can be approximated using:

$$u = \frac{\pi H}{T} \frac{\cosh k\ (y + d)}{\cosh kd} \cos \omega t \quad , \tag{4}$$

and

$$\frac{\partial u}{\partial t} = - \frac{2\pi^2 H}{T^2} \frac{\cosh kd\ (y + d)}{\sinh kd} \sin \omega t \quad , \tag{5}$$

where $k = 2\pi/L$ and $\omega = 2\pi/T$ are the wave numbers, y is the vertical coordinate measured upward from the bottom, d is the water depth, H is the wave height, T is the wave period, and L is the wavelength.

Expanding equation (4), the force exerted on a section of a pipe, dz, at any position z becomes:

$$\frac{df}{dz} = \frac{\pi^2 \rho D H^2}{2T^2} [-f_i \sin \omega t \pm f_D \cos^2 \omega t] \quad . \tag{6}$$

The overturning moment about the bottom according to Morison, et al., (1950) is:

$$M = \int_o^y (d + z)\, df = \frac{\rho D H^2 L^2}{T^2} \left(\frac{-\pi D}{4H} \cdot C_M K_1 \sin\omega t \pm C_D K_2 \cos^2 \omega t \right). \tag{7}$$

Because the small-amplitude theory underestimates u in shallow water, substitute the empirical stream function theory of Dean (1965) using cases 5-B and 3-B (Dean, 1975) for illustration (Figs. 2 to 6). Case 5-B represents the deepest water in which the sled is operated; case 3-B represents the breaking wave conditions.

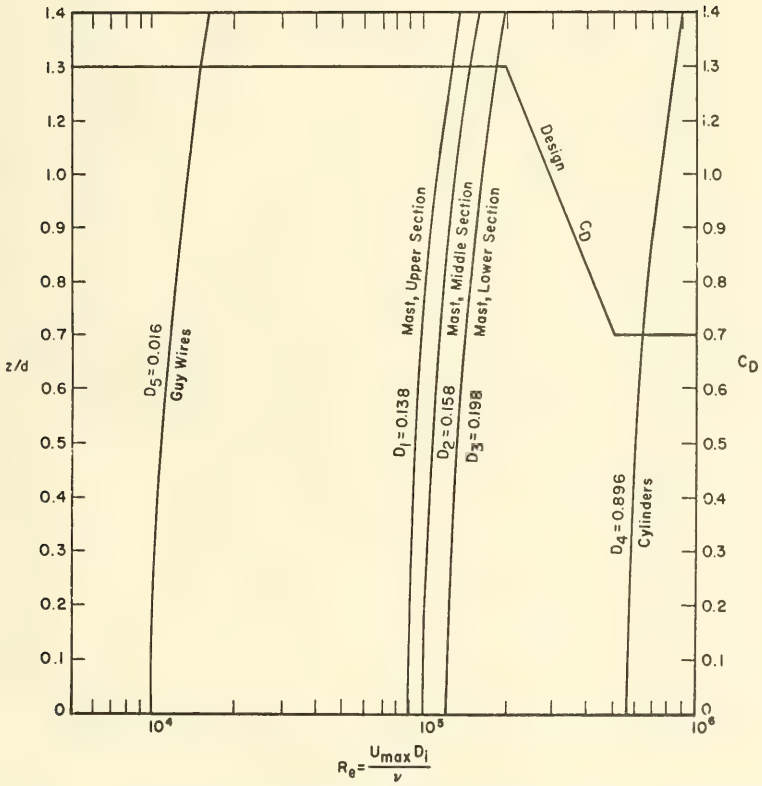


Figure 2. R_e versus z/d versus C_D (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975; Fig. 7-58).

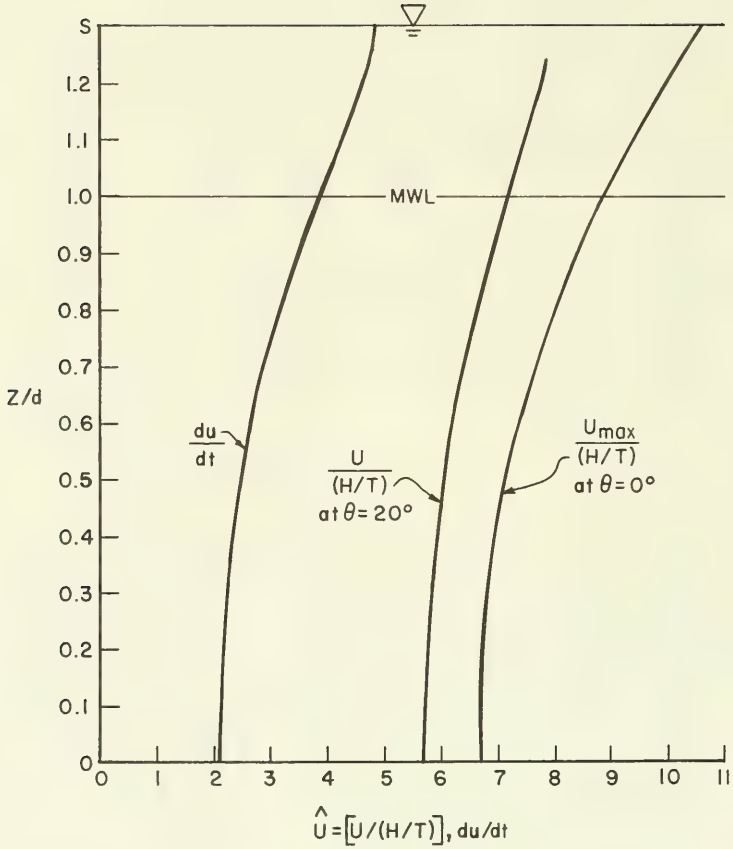


Figure 3. Distribution of $\frac{U_{max}}{(H/T)}$, du/dt, case 5-B.

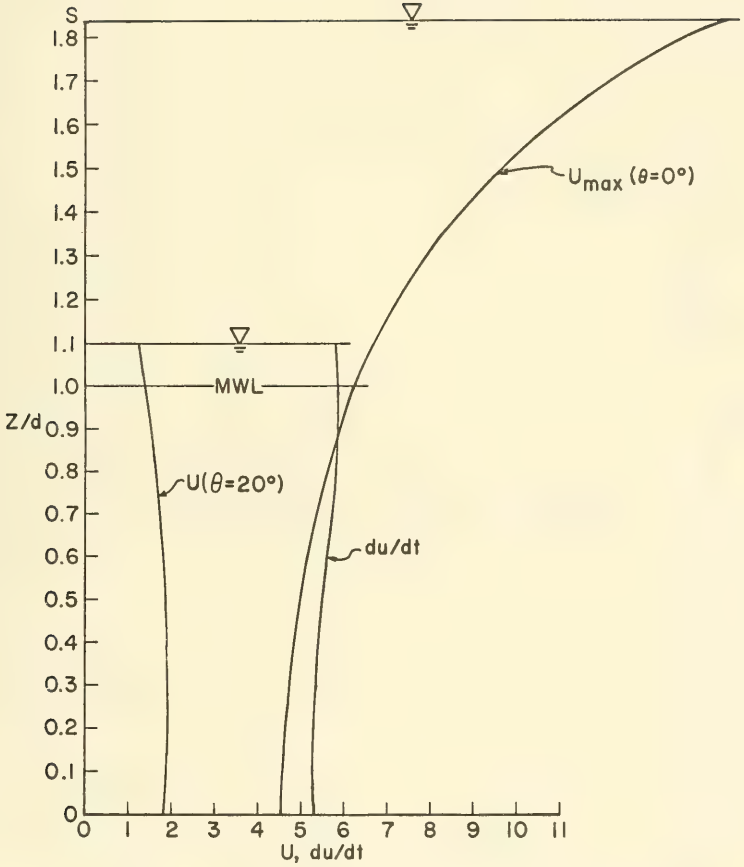


Figure 4. Distribution of U_{max}, du/dt, case 3-D.

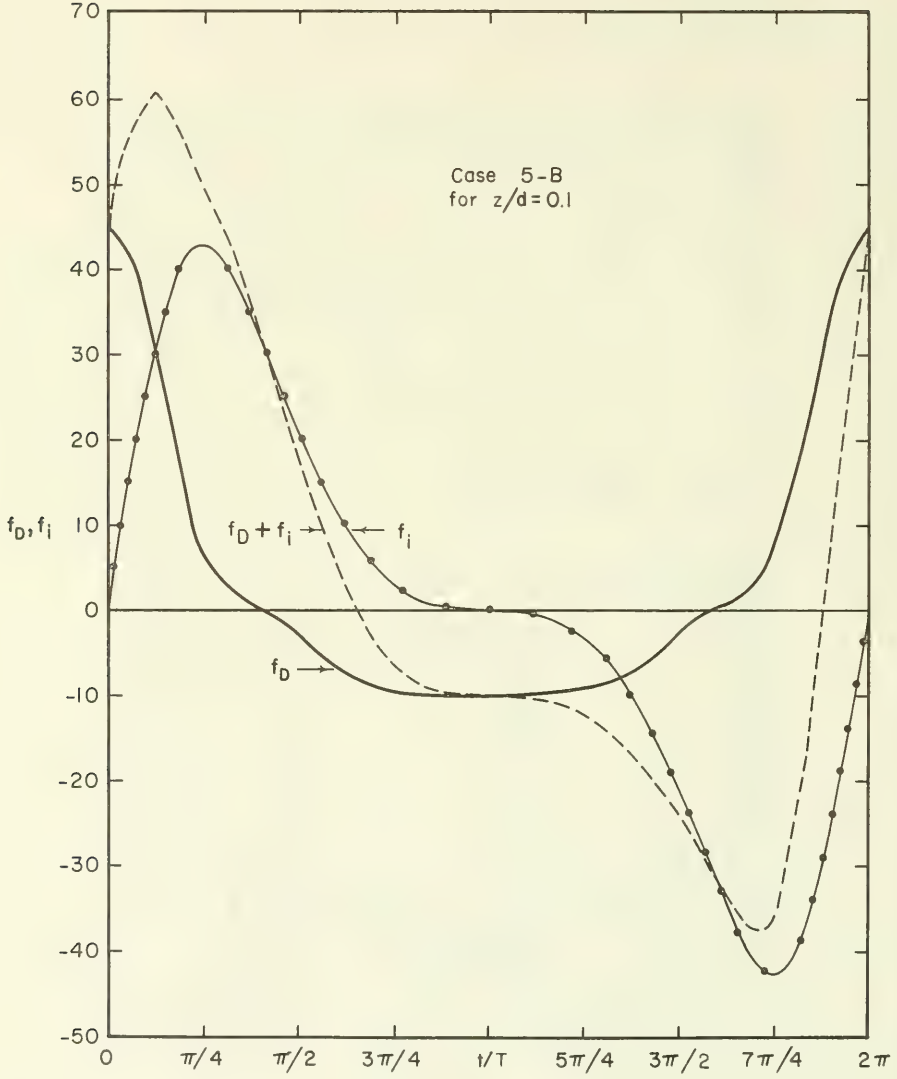


Figure 5. Case 5-B, f_D and f_i versus phase angle.

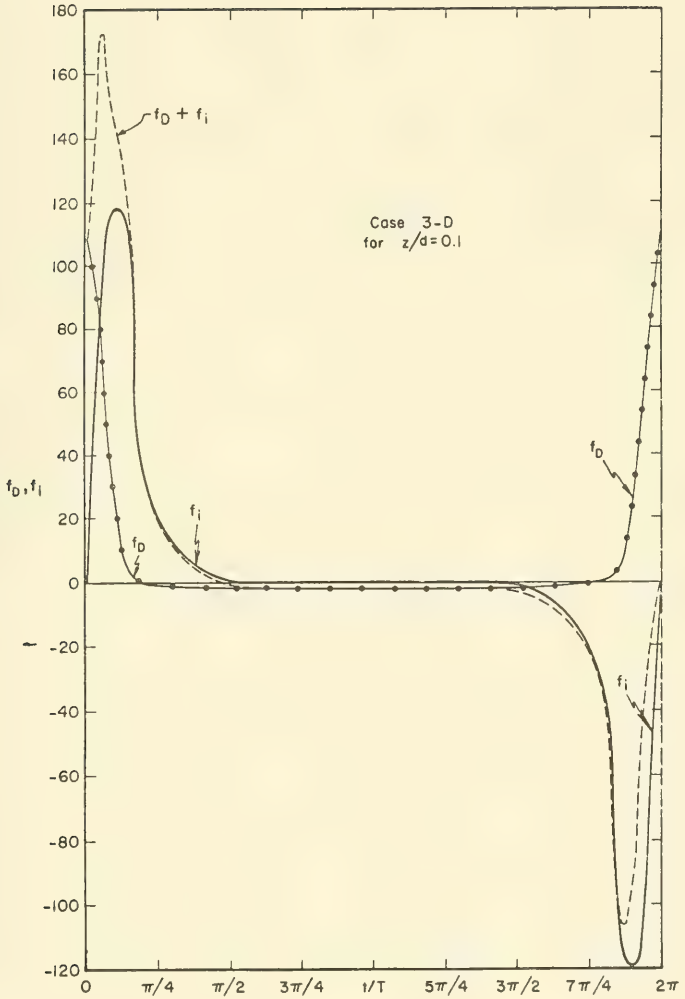


Figure 6. Case 3-D, f_D and f_i versus phase angle.

Members used in the sled construction with components contributing to f_D and f_i, have "pipe-equivalent" diameters in the range 4.87 millimeters (0.016 foot) < D_i < 27.3 centimeters (0.896 foot). The distribution of Reynolds numbers dependent on D_i is:

$$Re = \frac{U_{max}\ (\theta)i\ D_i}{\nu} \quad , \tag{8}$$

with a kinematic viscosity of 9.29 X 10^{-3} square centimeters per second^{-1} (1 X 10^{-5} square feet per second^{-1}) (Fig. 2) indicates the steady flow C_D = 1.2 is applicable in all but the case of the two cylinders. The variation of Re in the vertical is the result of the variation of U_{max} (θ = 0°) with depth, for case 5-B (Fig. 3) and for case 3-D (Fig. 4). Figures 3 and 4 also show the depth-dependent distribution of the horizontal acceleration for θ = 20° which is near the maximum for f_i. As f_{Dmax} and f_{imax} are not in phase (Figs. 5 and 6), the maximum total force on the sled can vary (θ = 22° to 45° when f_i is nonnegligible). The maximum force corresponding to the wave crest is always larger than the maximum under the trough of the wave.

The representative wave parameters for case 5-B are H = 3.53 meters (11.6 feet), T = 12.25 seconds, and d = 9.14 meters (the normal limit of seaward excursion). The total drag force, calculated for case 5-B is f_D = 4,151.2 newton and the inertia force is 168.3 newton; this is balanced by the submerged weight of the sled (225.89 kilograms or 498 pounds). The overturning moment, combining both f_D and f_i, is 18,853 newton meters (8,741.6 foot pounds) against 2,886.65 newton meters (2,196.8 foot pounds) resistance along the short axis of the sled, and 3,376.44 newton meters (2,490 foot pounds) in the direction of towing. Therefore, the sled will be unstable under these wave conditions.

In the examples of breaking wave conditions (case 3-D), only a part of the sled is submerged. The overturning moment along the short axis is 1,115.58 newton meters (822.7 foot pounds) (inertia forces not contributing), balanced by 2,978.86 newton meters (2,196.8 foot pounds) of resistance. This demonstrates that the sled is operable in 1.52-meter depths (5 feet) and 1.34-meter-high (4.38 feet) breakers at T = 10 seconds, commonly encountered under fair-weather conditions in coastal areas.

The above examples demonstrate that the danger of overturning in deep water is greater than in the breaker zone. Where the combined forces become excessive the corresponding sea state usually prevents operations *a priori*. However, with the sled parked offshore for continuous measurements, the possibility of loss in changing wave conditions is real.

b. Construction and Materials. The two main functional components of the sea sled are combinations of a mast and spars used to support oceanographic instrumentation and a pair of runners on which the device slides along the ocean floor. The runners are constructed of a 1.27-centimeter (0.5 inch) aluminum plate, a 7.62- by 1.5-centimeter (3 by 1.5 inches) aluminum channel, and a 8.89-centimeter-diameter (3.5 inches) aluminum pipe. The center platform is 0.61 meter (2 feet) square, constructed

of 0.635-centimeter (0.25 inch) aluminum plate, and welded to two 7.62- by 3.81-centimeter (3 by 1.5 inches) cross channels (Fig. 7).

An additional cross channel is attached across the edge of the runners. The 9.14-meter-high mast consists of three sections. The lower section is a 6.03-centimeter (2.375 inches) outside diameter 2.77-meter-long (9.08 feet) aluminum pipe; the middle section is a 4.82-centimeter (1.9 inches) outside diameter, 3.03-meter-long (9.96 feet) pipe; and the upper section is 3.34-centimeter (1.315 inches) outside diameter, 3.04-meter-long (9.98 feet) aluminum pipe. These sections are connected by coupling joints and the bottom of the mast is attached to a flange on the center platform. The mast is guyed at 12 points, in groups of four guys each at elevations of 3.048, 6.096, and 9.14 meters (10, 20, and 30 feet), and supports three or more adjustable spars to which the current meters are attached.

All members were constructed from extruded, aluminum alloy 6061-T6. Aluminum is preferable because of weight and corrosion resistance; the 6061-T6 alloy also has higher tensile strength than other alloys. The corrosion resistance is not affected by welding although there is some loss of strength in the weld area or heat-affected zone. Alloy 6061-T6 is the least expensive of all the heat-treatable alloys produced.

Where magnetic fields are present, stainless steel is not preferred to aluminum (see discussion of current meters); also, aluminum better absorbs impact loads from waves.

Erection of the structure takes about 2 hours and requires no specialized tools for assembling. The main structure is similar to equipment used in nearshore surveying; the difference being the spars, the skid design, and the instrument powerpacks. The sled's weight is increased by bolting steel bars to the runners, preferably to the bow part.

Damaged sections of the sled can be repaired at the field site with an arc welder.

c. Operation Modes and Required Support. Two standard operations have been practiced with the sled, the choice depending on the type of flow-measurement experiment. One operation is locating the sled at a desired point offshore and measuring currents *in situ*; the other requires towing of the device by a LARC V or LARC XV (lighter amphibious resupply cargo) vehicle along a given profile, usually alined normal to shore. The latter operation is an incremental movement of the platform, usually commencing in 9.14 meters of water to avoid submerging the antenna, and currents are measured for a given length of time at stations in sequence along the profile. During operation in this mode, the sled is decoupled from the LARC during recording time to prevent any movement of the sled due to drifting of the LARC. This procedure is repeated for each successive position of the sled along the profile (positions are usually precalculated). A pair of shore targets normal to the profile gives the LARC operator his control when moving in on the profile. Actual locations

Part	Part Number
RUNNER ASSEMBLY	
Bottom Plate	1
Channel	2
Spacer	3
Bearing Plate	4
Brace	5
Guy Cable Anchor	6
Skirt	7
PLATFORM ASSEMBLY	
Cross Channel	8
Cross Member Support	9
Cross Member Connector Plate	10
Brace Connector Plate	11
Platform Plate	12
Mast Support Plate	13
Mast Support Tube	14
Mast Support Brace	15
Cradle Anchor	16
Cradle Anchor	17
Platform Brace	18
Cradle Spacer	19
FRONT CROSS MEMBER	
Cross Channel	20
Cross Member Connector Plate	21
Brace Connector Plate	22
Tow Cable Connector Plate	23
REAR CROSS MEMBER	
Cross Channel	24
Cross Member Connector Plate	25
Brace Connector Plate	26
MAST ASSEMBLY	
Lower Section	27
Middle Section	28
Upper Section	29
Upper Couple	30
Lower Couple	31
Couple Guy Anchors	32
Upper Mast Guy Anchor	33
Upper Spar	34
Middle Spar	35
Lower Spar	36
Spar Mount	37
Turnbuckles	38
Guy Cable	39
CYLINDER CRADLE	
End Plate	40
Channel	41
Base Plate	42
Brace	43
POWER PAK CYLINDER	
Main Cylinder	44
Flange	45
Lid	46
Handle	47
Bulkhead Connector	48
ELECTRONICS CYLINDER	
Main Cylinder	49
Flange	50
Lid	51
Handle	52
Bulkhead Connector	53

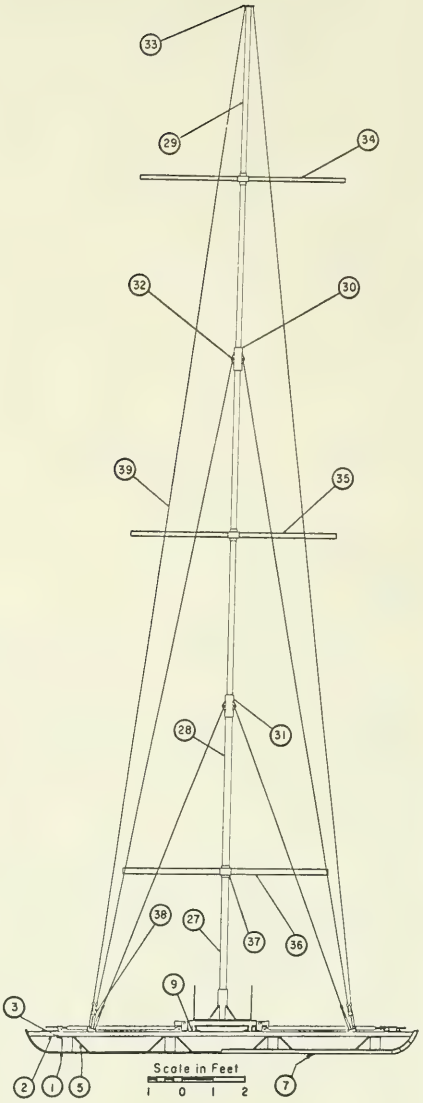


Figure 7. Engineering drawing of sea sled.

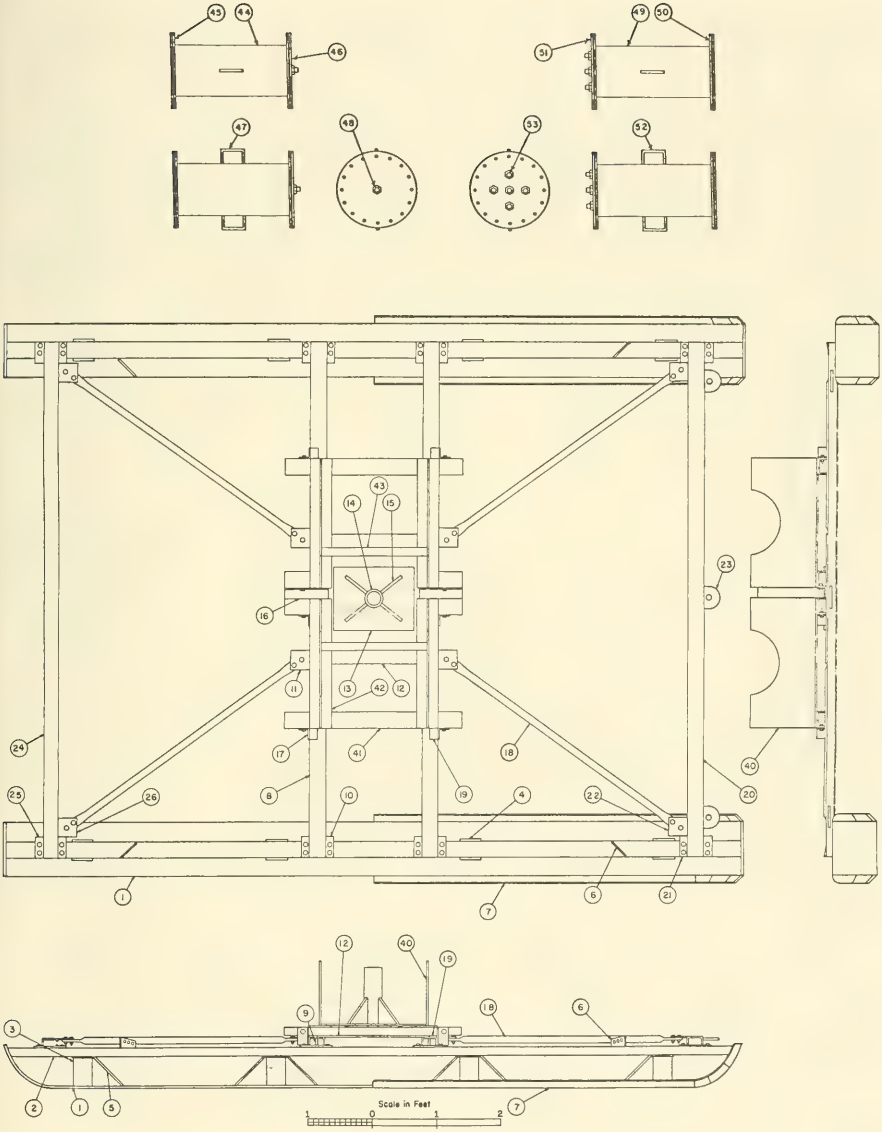


Figure 7. Engineering drawing of sea sled (continued)

of the sled on the profile line are determined with transits while recording is taking place.

The sled is towed with a 0.794-centimeter-diameter (0.3125 inch) galvanized steel cable coupled to harnesses on the sled and on the LARC. Cable lengths vary depending on the mode of operations. Several 30.48- and 91.44-meter (100 and 300 feet) sections of cable which can be attached consecutively are carried onboard the LARC. About 152.4 meters (500 feet) of cable are needed to turn the sled around in depths of 9.14 to 15.24 meters (30 to 50 feet) and to aline the sled on a profile headed toward the shore. Care must be taken when using shorter lengths of cable since the sled has a tendency to hydroplane and could possibly capsize if an obstruction was hit. Extra cable is also added to avoid coupling and decoupling when passing through the surf zone.

While the sled is under tow, a minimum of two people are needed, a LARC operator and a deckhand. Experimental designs requiring these operations are discussed in the next section.

2. Instrumentation.

The sea sled was principally designed for deploying current meters in depths not over 9.14 meters. The sled's most important assets are the versatility of measurements provided by the spars which can be raised, lowered, or rotated, and the current-meter mounts which are also adjustable to alinements on any of three axes. Thus, sensors can be placed in any configuration and at any elevation below 9.14 meters. In practice, the sensors are seldom placed closer than 0.91 meter (3 feet) of the bottom because streaming around the cylinders is expected to bias records produced by the sensors. In addition to the current meters, a pressure wave gage is commonly installed on the sled. However, the number and kinds of instruments are not limited by the sled, as long as a method to collect the data from the instruments is provided.

Realining a sensor or moving it from one elevation to another can be executed underwater by a diver. This operation requires the loosening of setscrews of the cross fittings which support the spars.

Upward or downward movement is limited to each 3.048-meter length of each section of the mast. While the spars can be rotated in horizontal plane or about their axes, the current meters can also be rotated 360° about the spar axis; this is easily done even underwater by loosening a pair of U-bolts holding the mount. If necessary, the sensors can also be moved laterally. Rotation about the spar, if alined normal to shore, will change a shore-parallel recording to a vertical or vice versa; to aline in a shore-normal position will require complete removal of the mount and the attached sensor (Fig. 8).

a. Current Meters. Of the four types of current sensors commonly in use (acoustic, inductance (EM), force, and mechanical), the mechanical current meters are the most reliable in the surf zone. The principle of

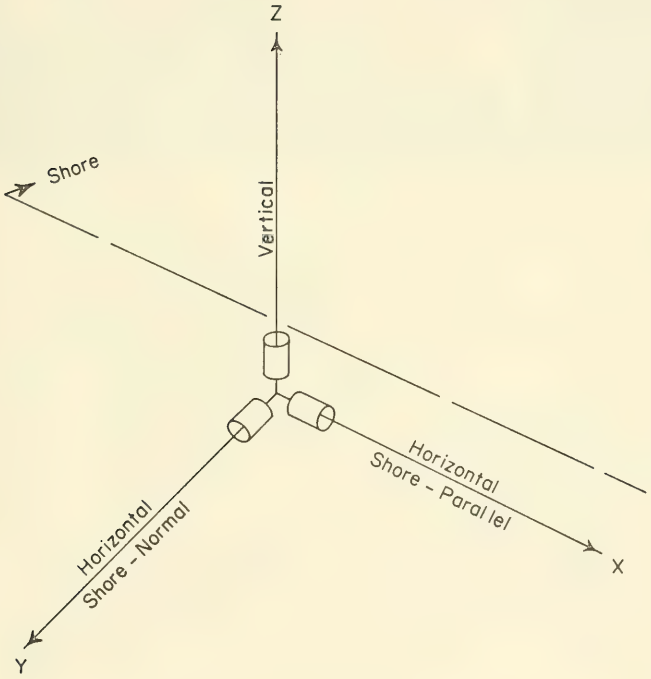


Figure 8. Reference axes for sensor alinement.

operation is to channel flow across an impeller mounted in a duct (Fig. 9). Magnets embedded in the blades of the impeller close reed switches, and in a bidirectional sensor the switching sequence (Fig. 10) determines the direction of flow.

Ducted, impeller current meters by Bendix were used in experiments during the last 3 years. The first set of meters had four-blade impellers in a 7.62-centimeter (3 inches) duct (Bendix Model B-7) modified for bidirectional response (Fig. 11); the second set of four meters (Bendix Model B-10) was designed to be bidirectional sensors with five-bladed impellers in 10.16-centimeter (4 inches) ducts. In the latter model, range is 0 to 5 knots (0 to 257 centimeters per second) with a threshold velocity of 2 centimeters per second. In the range 1 to 100 pulses per second, meter response is linear (Fig. 12). For calibration purposes, 16 pulses per second equal to 1-knot current is used.

b. Wave Gage. Measurement of the height and period of waves, concurrently with the sensing of current speed, is obtained from a pressure wave gage (Fig. 13). This instrument consists of a solid state, strain gage pressure transducer with a range of 0 to 11.34 kilograms per square centimeter-absolute (0 to 25 pounds per square inch-absolute) and housed in a 0.63- by 27.3-centimeter (2.0625- by 0.896-foot) (outside diameter) aluminum cylinder. The gage senses the total pressure at a given depth from which the dynamic pressure component is extracted and used as the measure of wave height given the pressure correction factor at that location. Since it is difficult to determine the pressure correction under various conditions of shoaling waves, the gage is usually mounted adjacent to one or more current meters which provide an independent estimate of the correction factor. The wave gage is designed to switch ranges in increments of 3.048-meter depths with a ±0.61-meter overshoot. This gage was designed at CERC, and permits conduct of continuous surveys in variable water depths to a maximum of 9.14 meters.

c. Auxiliary Instrumentation. A comprehensive coastal oceanographic experiment usually requires the measurement of several additional parameters, such as windspeed and direction, barometric pressure, salinity, and water temperature. The TODAS is capable of accommodating these future requirements in one of two ways. Sensors can be added to the sea sled part of TODAS, thereby requiring only the installation of one voltage-controlled oscillator (VCO) for each new sensor (assuming an output of 0 to 5 volts (direct current)). Signals from these sensors can be mixed and demodulated in the same fashion as for existing current meters and the wave gage. One frequency discriminator has to be installed at the receiving unit for each sensor.

Another capability of TODAS is the direct input of signals from sensors not housed on the sled (e.g., from a shore-based anemometer). The signal input, in this case, can be either analog or digital (Binary Coded Decimal-BCD) format; a total of 32 sensors can be accommodated.

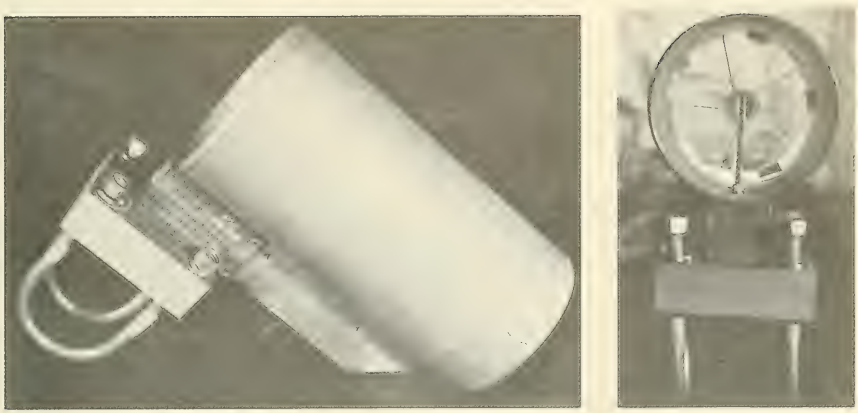


Figure 9. B-10 current meter with schematic.

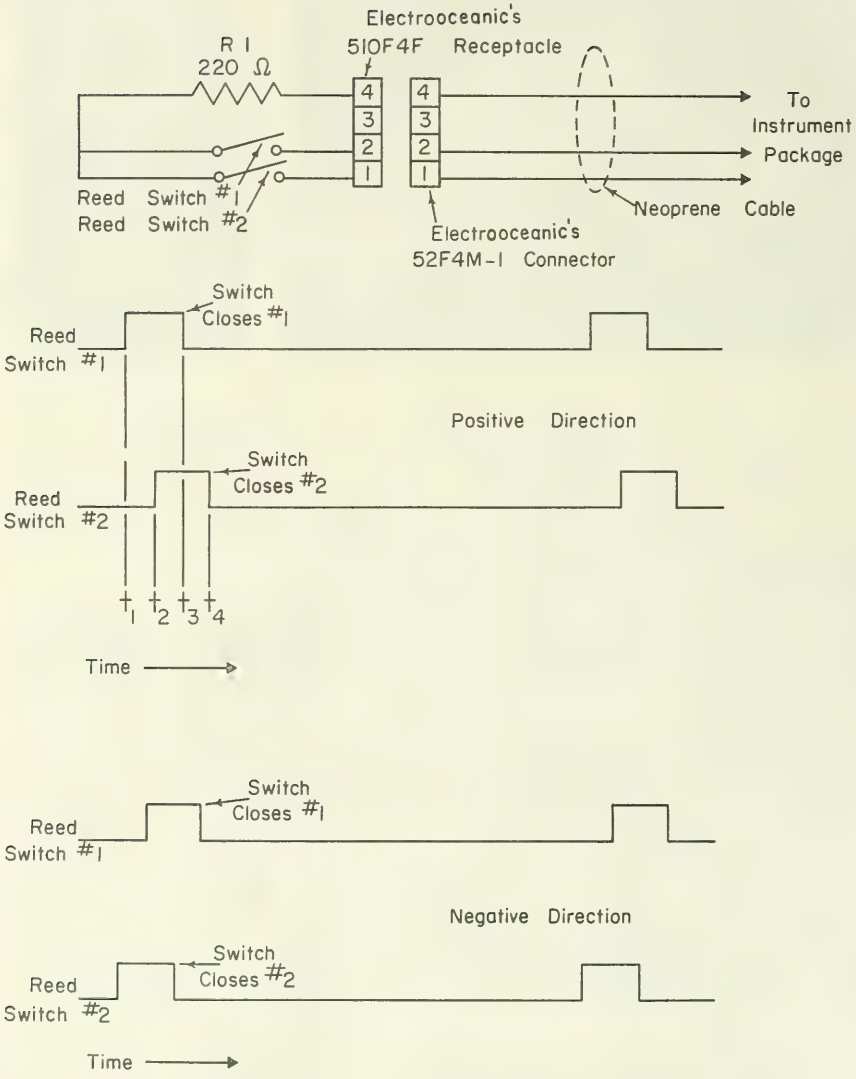


Figure 10. Reed switches and closure sequence.

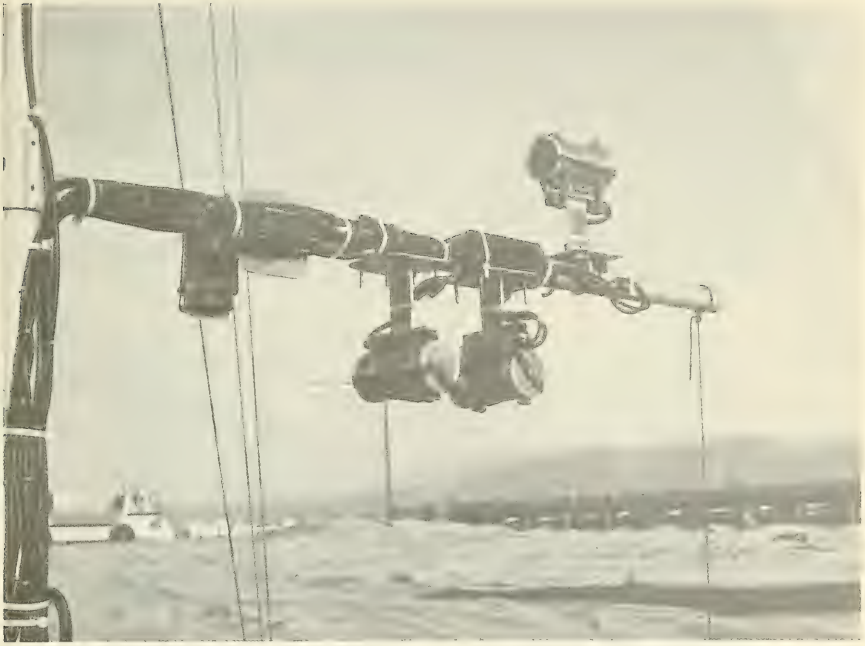


Figure 11. B-7 sensor.

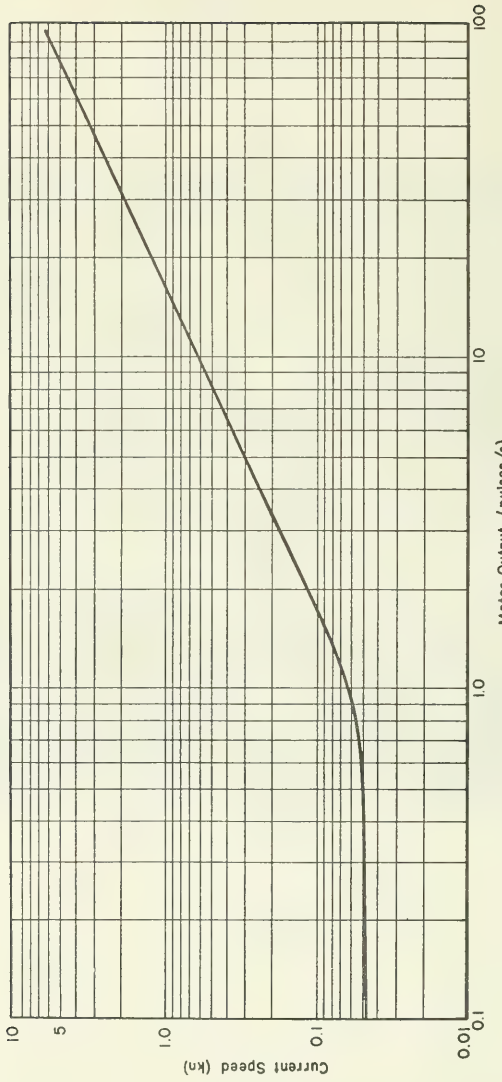


Figure 12. Response curve, B-10 sensor.

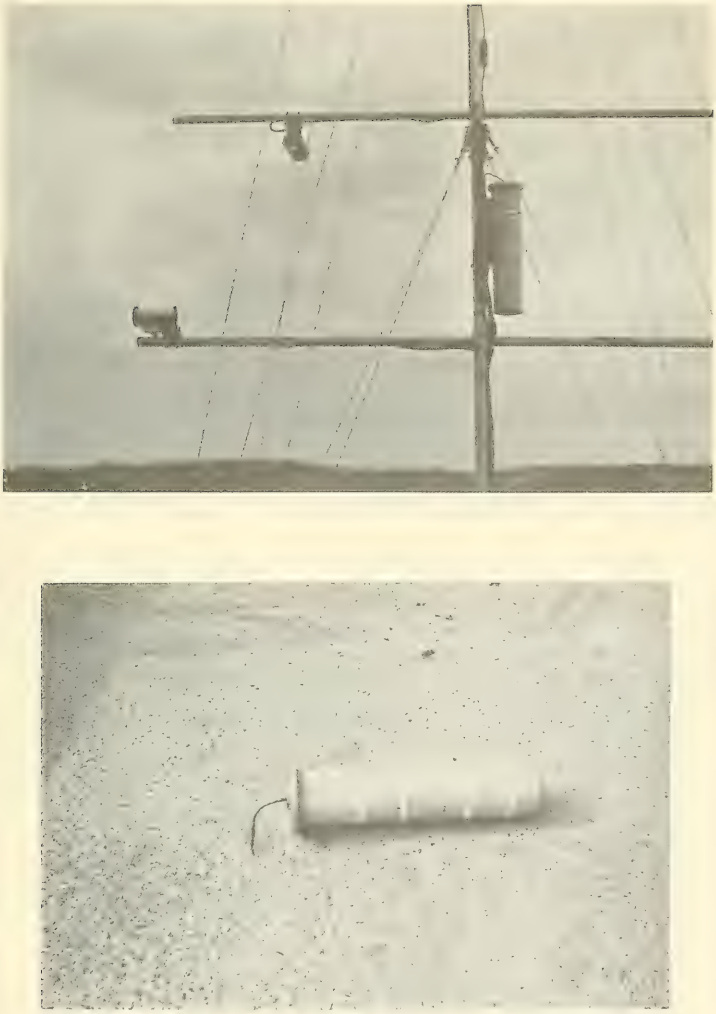


Figure 13. Photos of wave gage.

III. POWER REQUIREMENTS

TODAS was designed to operate on a direct-current power supply which would give experimental capability in remote localities. In previous experiments, either a conventional source or a portable generator (alternating current) was used to avoid the problems of handling and charging batteries. During field experiments, a small portable gasoline-powered generator proved adequate for operating the receiver, discriminator, data logger, analog, and digital recorders. The power consumption of the onshore system is about 7 amperes per hour.

All components onboard the sea sled are powered by four 12-volt rechargeable Gel Cell batteries housed in an aluminum cylinder (0.63 by 27.3 centimeters, outside diameter) that rides on the sled (Fig. 14). Each battery is rated at 20 ampere-hours, giving a total of 80 ampere-hours (equivalent to 260 hours) continuous underwater operation without recharging. The battery and instrument package are connected by an eight-conductor neoprene cable with bulkhead connectors (Fig. 15).

1. Electronics.

In an earlier version of the present system, all data were obtained, processed, and recorded as analog signals (voltage) onboard the sled. Since this system precluded real-time observation of the data flow needed for appraising the performance of sensors and for determining whether significant values of ocean parameters are being recorded, modifications were undertaken which separated data acquisition into onboard (on the sled) and onshore components.

a. Signal Acquisition, Mixing, and Telemetry. Outputs of the current meters are dual overlapping pulses which are converted to an analog signal (± volt, direct current) by the signal-conditioning circuitry, one for each sensor (Fig. 16 and App.). The processed signals are amplified to match the input of the VCO and then mixed before being relayed to the transmitter (Fig. 16). Pulse to analog conversion, amplification, analog to frequency conversion, and mixing take place within the instrument package housed inside an aluminum cylinder (0.61 meter long by 27.3 meters in diameter) which rides on the sled (Fig. 17).

Output of the pressure wave gage (0 to 5 volts, direct current) and the direct-current signals from each current meter are converted into frequencies by the VCO's, mixed through a series of operational amplifiers, and transmitted to a shore-based receiver on 27.454 megahertz frequency band. The transmitter, with its antenna mounted at the top of the mast, has a power output of 2.2 watts (Fig. 18). Effective operational limits of the telemetry system is about 8.05 kilometers (5 miles). Radio noise becomes a problem beyond this distance.

b. Receiving and Demodulation. The modulated signals are usually received onshore (Fig. 19) (although signals can also be received on the

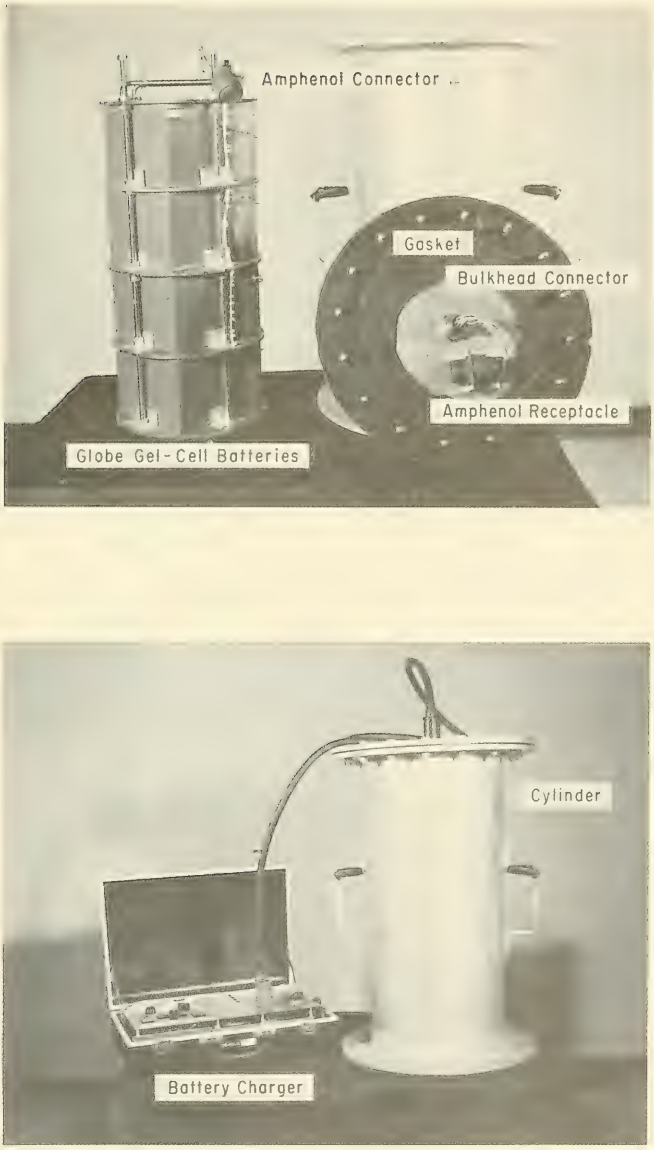


Figure 14. Batteries (upper photo), charger, and cylinder (lower photo) for power package.

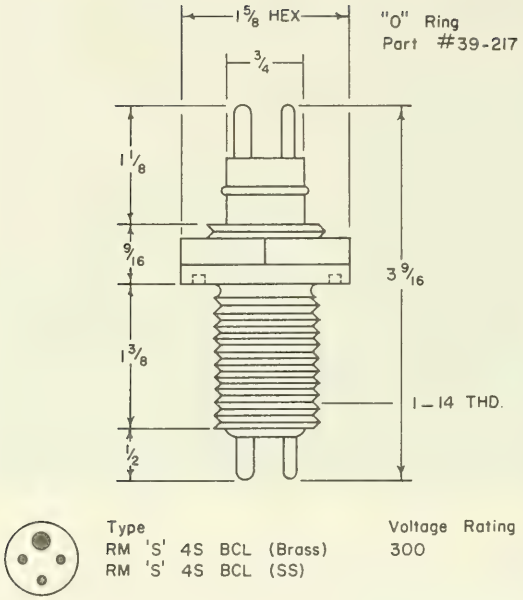


Figure 15. Bulkhead connectors.

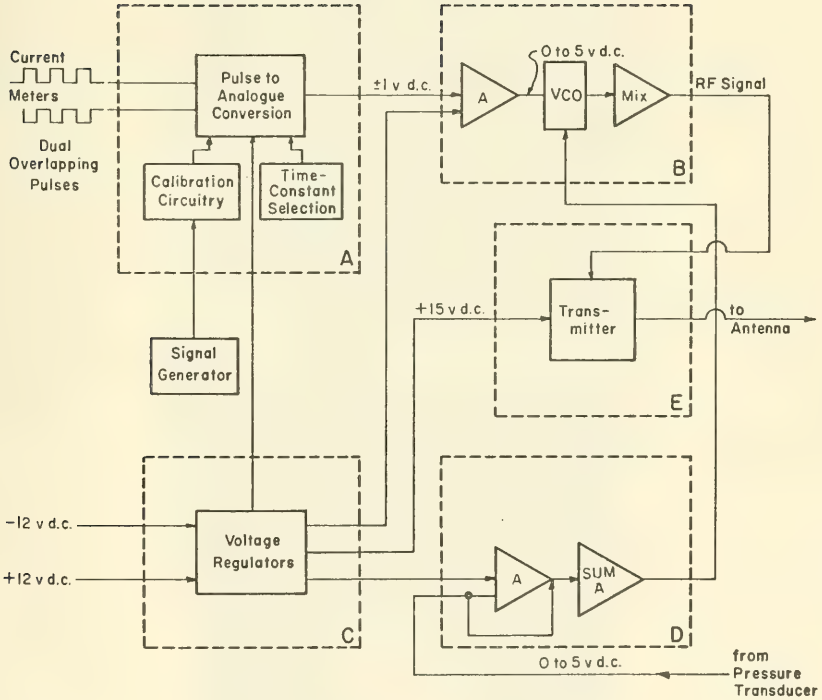


Figure 16. Generalized schematic of onboard electronics (letters refer to enlarged schematics in Appendix).

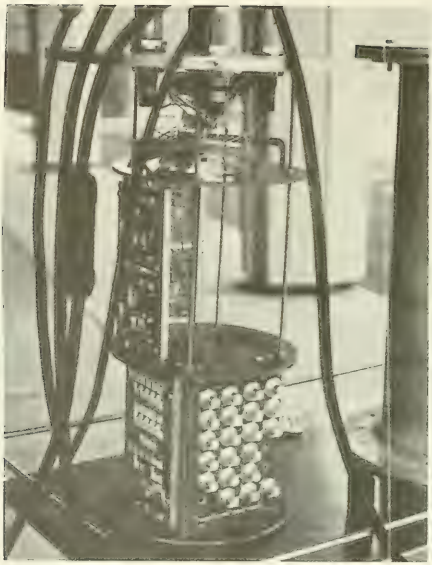


Figure 17. Instrument package and cylinder.

Figure 18. Transmitter.

Figure 19. Onshore electronics.

towing vessel), and discriminated according to channel number and information content. The discriminated signals are monitored on a six-channel analog recorder for real-time visual observation and for a permanent continuous record.

c. Analog-Digital Conversion and Recording Modes. Output from the discriminators enters a data logger consisting of several major parts (Fig. 20). The data logger converts the analog signals to digital form, assigns the time to the data points, identifies the channels (sensors), and outputs the digitized data for recording on magnetic tape.

The data logger (Fig. 21) is a portable alternating or direct current-powered analog to digital converter scanning up to 32 analog channels at the rate of 33.3 channels per second, converting 200 characters per second, each character having six BCD bits. Analog multiplexing is done with COSMOS switches. The unit accepts up to 12 parallel bits of external data recorded in 10 (4-bit) bytes.

The main feature of the data logger is the system's variable scan rate (Table 1) of 0.333, 1.667, 3.333, 8.333, 16.7, and 33.3 channels per second (BCD formating), limited by the tape recorders' 300-character per second recording speed. Other recorders are available with: higher scan rates up to 1,000 channels per second; 2^0 and 2^4 to 2^{12} scans per record and records per file; single, continuous and monitor-scanning modes; automatic start at intervals of 10^0 between 10^{-2} and 10^1 seconds, 1, 5, 10 minutes, and 1, 2, and 24 hours with an interval multiplier of 1 to 9 (Table 2); choice of end of record (EOR), end of file (EOF) or no stop, visual monitoring of data and time automatic and manual channel advance, and inter-record gap (IRG) or file gap control.

Table 2. Timed start intervals.

Time Base (Multiplier)	0.01 (s)	0.1 (s)	1 (s)	10 (s)	1 (min)	5 (min)	10 (min)	1 (h)	2 (h)	24 (h)
1	0.01	0.1	1	10	1	5	10	1	2	1
2	0.02	0.2	2	20	2	10	20	2	4	2
3	0.03	0.3	3	30	3	15	30	3	6	3
4	0.04	0.4	4	40	4	20	40	4	8	4
5	0.05	0.5	5	50	5	25	50	5	10	5
6	0.06	0.6	6	60	6	30	60	6	12	6
7	0.07	0.7	7	70	7	35	70	7	14	7
8	0.08	0.8	8	80	8	40	80	8	16	8
9	0.09	0.9	9	90	9	45	90	9	18	9

Data are recorded on a seven track, 556 bits per inch magnetic tape recorder (Fig. 22) which operates on either 110 volts (alternating current) or 12-volts battery power. Data are recorded on 1.27-centimeter-wide tape

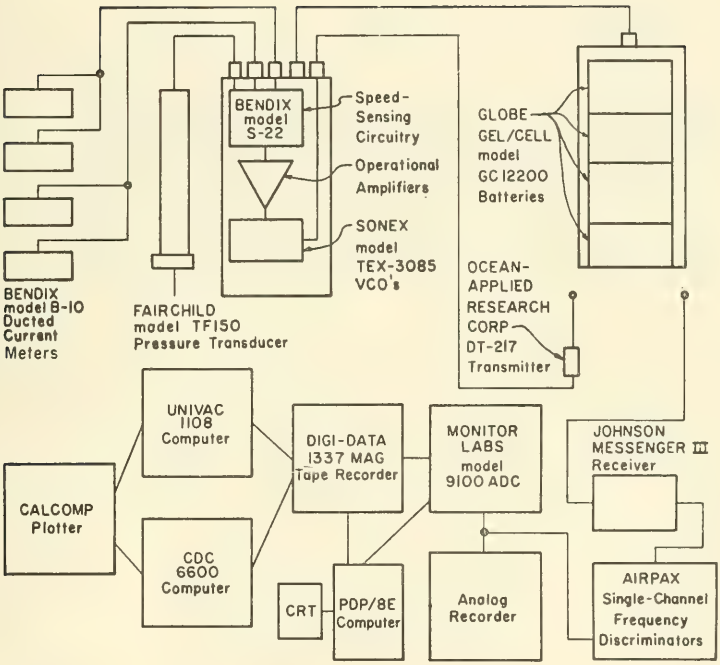
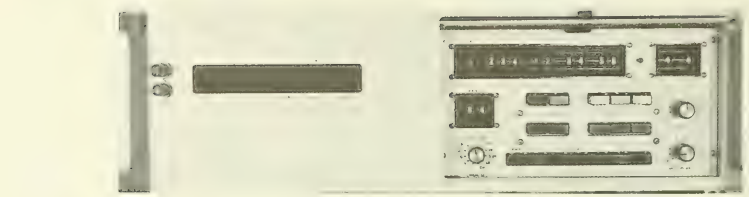


Figure 20. Flow diagram, instrument components.



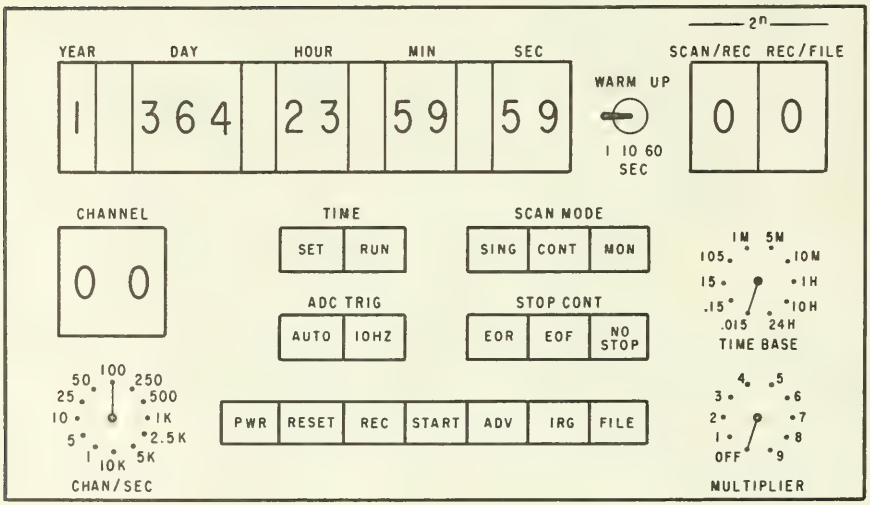


Figure 21. Data logger with enlargement of control and monitoring panel.

Table 1. Scan rate selections.

Switch position (chan/s)	Data format characters	Character rate (character/s)	Actual rate (chan/s)	Applicable Recorder Options, MP					
				3-1	3-2	3-3	3-4[1]	3-5	3-6
1	2	2	1	X	X	X	X	X	X
	4	2	0.5	X	X	X	X	X	X
	6	2	0.333	X	X	X	X	X	X
5	2	10	5	X	X	X	X	X	X
	4	10	2.5	X	X	X	X	X	X
	6	10	1.667	X	X	X	X	X	X
10	2	20	10	X	X	X	X	X	X
	4	20	5	X	X	X	X	X	X
	6	20	3.333	X	X	X	X	X	X
25	2	50	25	X	X	X		X	X
	4	50	12.5	X	X	X	X	X	X
	6	50	8.333	X	X	X	X	X	X
50	2	100	50	X		X		X	
	4	100	25	X	X	X		X	X
	6	100	16.7	X	X	X	X	X	X
100	2	200	100	X		X		X	
	4	200	50	X		X		X	
	6	200	33.3	X		X		X	X
250	2	500	250					X	
	4	500	125					X	
	6	500	83.33	X		X		X	
500	2	1,000	500					X	
	4	1,000	250					X	
	6	1,000	167					X	
1,000	2	2,000	1,000					X	
	4	2,000	500					X	
	6	2,000	333					X	
2,500	2	5,000	2,500					X	
	4	5,000	1,250					X	
	6	5,000	833.3					X	
5,000	2	10,000	5,000					X	
	4	10,000	2,500					X	
	6	10,000	1,667					X	
10,000	2	20,000	10,000					X	
	4	20,000	5,000					X	
	6	20,000	3,333					X	

1. Option presently used.

Recording rate	0 to 300 characters per second
Packing density	556 bits per inch
Number of tracks	7
Tape width	0.5 inch
Parity	odd
Power	105 to 125 volts, 50 or 60 hertz, 1.5 amperes, 12 volts-direct current (switch selectable)

Figure 22. Magnetic tape recorder and specifications.

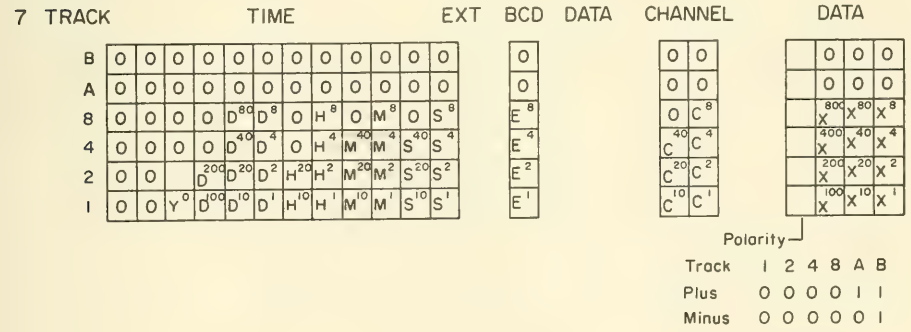
on 2.16-meter (8.5 inches) coplanar-mounted reels equivalent to 365.76 meters (1,200 feet) of 1.5-mil tape. Recording rate is 0 to 300 characters per second. Data formated as follows:

RECORD

FIRST POINT DATA (Date and Time)	DATA nCHANNELS	LAST POINT
OOYDDDHHMMSS	CCPXXX	0 IRG RECORD IRG RECORD

n RECORDS PER FILE

Symbols are: Y = year, D = day, H = hour, M = minute, S = second, C = channel number, P = polarity, and X = data. Each record is arranged according to code (each block signifies a bit):



Typical files are composed of 2^4 scans per record and 2^6 records per file, a total of 1,024 data points per channel. Generally, this is considered a convenient length of information for wave and current data, requiring 4 minutes and 55 seconds of recording time. A comparison of different settings for recording data (Table 3) indicates the time required to record 2^{10} data points per channel in the continuous mode can vary between 1,224 and 2,216 seconds. Records in excess of 2^{12} words are usually too long for time-series analysis.

2. System Calibration.

Several calibration procedures must be observed with TODAS. The first is calibrating the current meters for frequency response, accuracy in recording speed and directivity (cosine response), threshold velocity, linearity, and environmental response (ruggedness). Coupled to the frequency response and threshold velocity is the bidirectivity of the sensor, i.e., the

Table 3. Comparison of scans-record times records-file versus time of recording.

Scans-Record		2^0	2^4	2^5	2^6	2^7	2^8	2^9	2^{10}	2^{11}	2^{12}	
2^0	s[1]	1.5	10.0	18.0	36.0	70.0	140	227	554	1,108	2,216	1
	m[2]	0.025	0.16	0.3	0.6	1.17	2.33	4.62	6.23	18.5	36.9	
2^4	s	5.0	81.0	162	324	648	1,296	2,592	5,184	10,368	20,736	16
	m	0.08	1.35	2.7	5.4	10.8	21.6	43.2	86.4	169.2	338.4	
2^5	s	10.0	157									32
	m	0.16										
2^6	s	20.0										64
	m	0.33										
2^7	s	39.0										128
	m	0.65										
2^8	s	77.0										256
	m	1.28										
2^9	s	154.0										512
	m	2.56										
2^{10}	s	360										1024
	m	5.10										
2^{11}	s	612										2048
	m	10.2										
2^{12}	s	1,224										4096
	m	20.4										
		1	16	32	64	128	256	512	1024	2048	4096	

Data Points

1. Seconds.
2. Meters.

ability to record continuously across the line of zero flow from the negative to the positive domain. The threshold frequency determines how well the meter responds to the oscillatory flow under waves. However, an ideal sensor should equally be responsive to quasi-steady motions and the capillary wave range. The limiting factor for ducted meters is the inertia of the impeller's mass (and indirectly by the fit and wear of the bearings); the B-10 sensors response time to an impulse force is 0.1 second. The system has three options for the time constant, 0.22, 2.2, and 22.2 seconds.

Directivity of the meter, commonly referred to as a *cosine response*, is important for determining the velocity of the flow at the point of measurement, i.e., both the rate of flow through the sensor and its direction. Since the B-10 meters have near-cosine response, speeds recorded by three sensors placed in an orthogonal configuration can be resolved into a resultant vector representing velocity.

Information available on tests performed with the B-7 sensors (Fig. 11) discussed below demonstrates the utility of a directed, impeller-type meter for measuring currents which include wave components.

a. Laboratory Tests. Four B-7 current meters were tested in 1972 in a 29.26- by 0.457-meter (96 by 1.5 feet) wave tank in 0.61 meter of water. The sensors were attached to a carriage driven by a bulkhead frame with the bulkhead removed, and oscillated in still water using a programable wave generator. The reason for a simulated wave condition rather than real waves was to eliminate reflected waves from either end of the tank. Two amplitudes of the sine wave input (a_1 = 25.4 centimeters (10 inches) and a_2 = 50.8 centimeters or 20 inches) were used with frequencies of 0.05, 0.0625, 0.0714, 0.08, 0.1, 0.125, 0.0538, 0.2, 0.25, and 0.4 hertz. The sensors were tested for linearity of response, phase lag, voltage, and pulse output as functions of frequency and amplitude of oscillation.

Figure 23 shows that the relationship between the maximum voltage, A_{max}, and the corresponding maximum velocity, V_{max}, is linear:

$$V_{max}\ \left(\frac{cm}{sec}\right) = -1.499 + 1.983\ A_{max}\ (mV)$$

Since a high-frequency oscillation and a long time-constant preclude the output voltage to reach zero for zero velocity, the sensors' responses were evaluated with respect to the offset voltage which follows the relationship:

$$V_{max}\ \left(\frac{cm}{sec}\right) = 3.95 + 2.095\ A_{min}\ (mV)$$

as shown in Figure 24. The correlation coefficients were R^2 = 0.9955 and 0.9907, respectively. Calibration tests for the flow velocity versus pulses per second output of the B-7 sensors indicated that towing tank-generated response curves cannot be used in bidirectional flow conditions.

The phase-frequency relationship is a concern in oscillating flow, i.e. the real time associated with the function forcing the response recorded

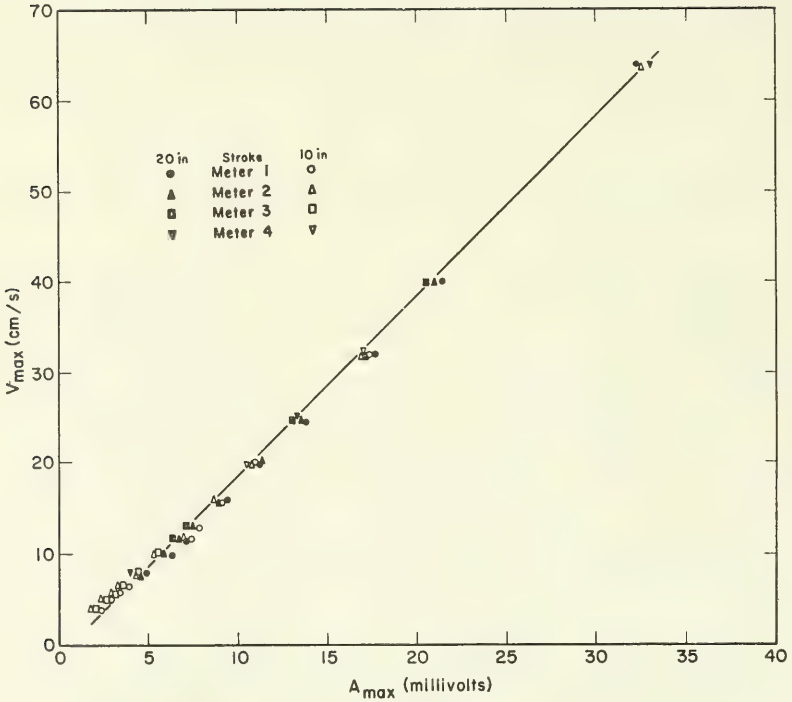


Figure 23. B-7 sensor, V_{max} versus A_{max}.

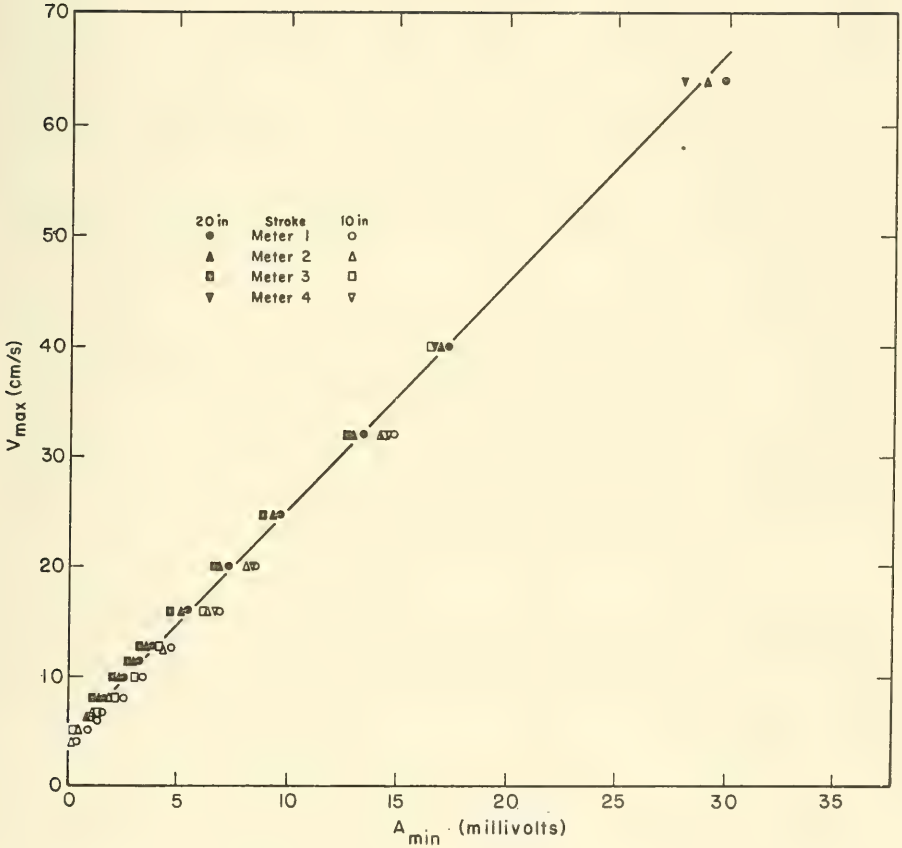


Figure 24. B-7 sensor, V_{max} versus A_{min}.

by the sensor must be known. Figure 25 shows that the response of the B-7 current meter is phase-dependent, and the lag (and scatter) increasing toward lower frequencies.

An extensive calibration test has been completed by National Oceanic and Atmospheric Administration (NOAA), National Oceanographic Instrumentation Center (NOIC) on the B-10 current meters. A later evaluation of the meters will be expanded to include prototype waves, environmental tests, response to vibration, and virtual mass effects. Results of the calibration test show a nearly true cosine response of the B-10 meters (Fig. 26).

The wave gage was calibrated statically, applying compressed air to the pressure transducer. The output voltage was then recorded as a function of pounds per square inch units of pressure.

b. Field Tests. Calibration of the circuitry is important in collecting good data. The following steps are observed before each deployment of the sea sled:

(1) Check power supply voltage output;

(2) calibrate current meter pulse to analog conversion circuitry with a 16-hertz source (16 hertz = 1 knot);

(3) check radio frequency output from voltage controlled oscillators;

(4) check radio frequency input to discriminators;

(5) check wave gage voltage output;

(6) check directional response of current meters; and

(7) record offset.

To verify that the performance of all current meters are identical under field conditions, the sensors are mounted side by side on one of the spars (Fig. 27) and towed offshore. Consequently, data are recorded for 3 to 4 orientations of the sled (with respect to the base line), thus evaluating if any differences in voltage output or phase are present in the meters.

IV. EXPERIMENTAL DESIGNS

Three experimental designs for the measurement of coastal currents and the corresponding operations are discussed in this section.

1. Continuous Surveys Along Shore-Normal Profiles.

a. Rationale and Needs. The purpose of surveying flow properties along a profile is threefold: (a) To record the variation in current magnitude near the surface or on the surface with distance from shore; (b) to record the spatial structure of currents near the boundary and

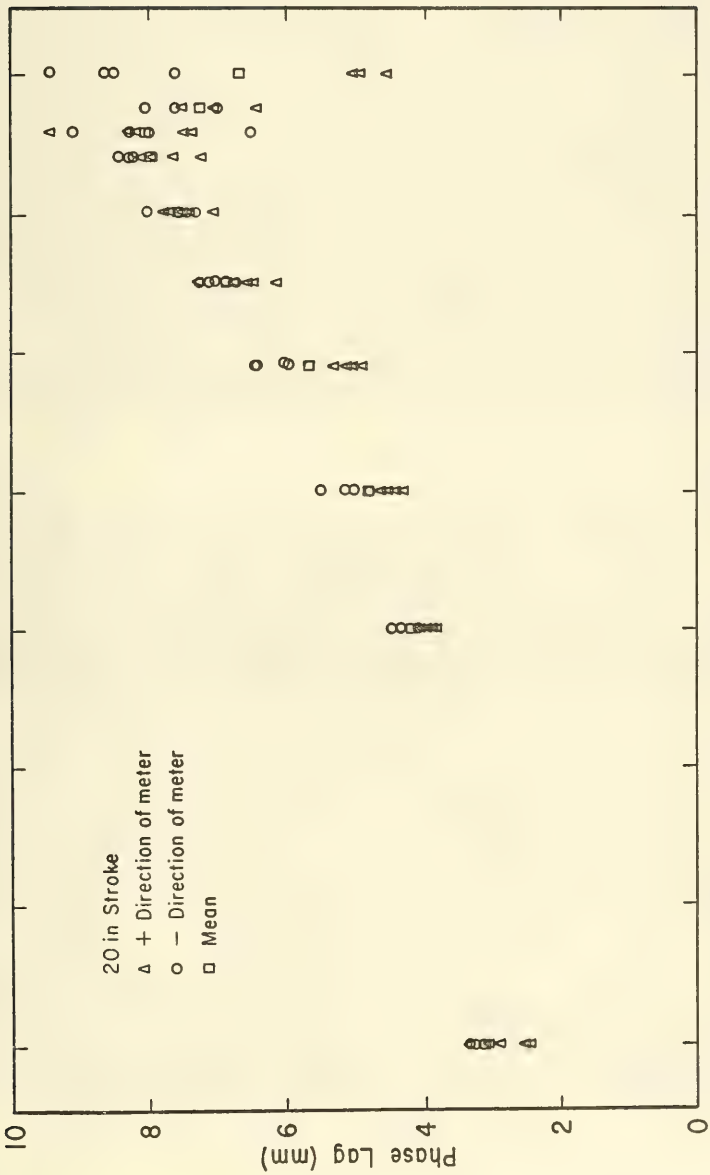
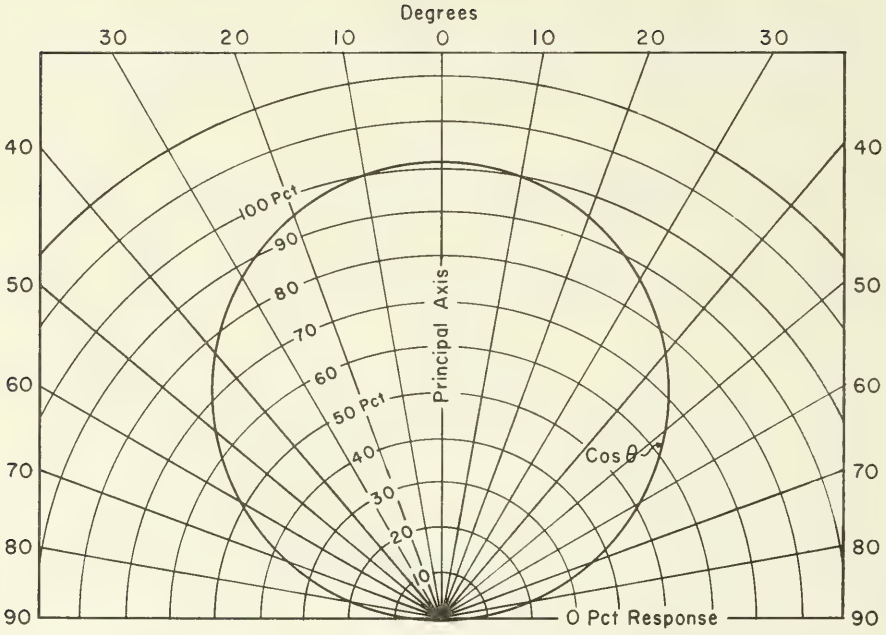


Figure 25. Phase lag versus frequency.



Degrees	Cos θ	B-10 Percent Response
10	0.984	0.974
20	0.939	0.934
30	0.866	0.868
40	0.766	0.763
50	0.643	0.627
60	0.500	0.496
70	0.342	0.349

Figure 26. True cosine response curve and actual B-10 sensor response.

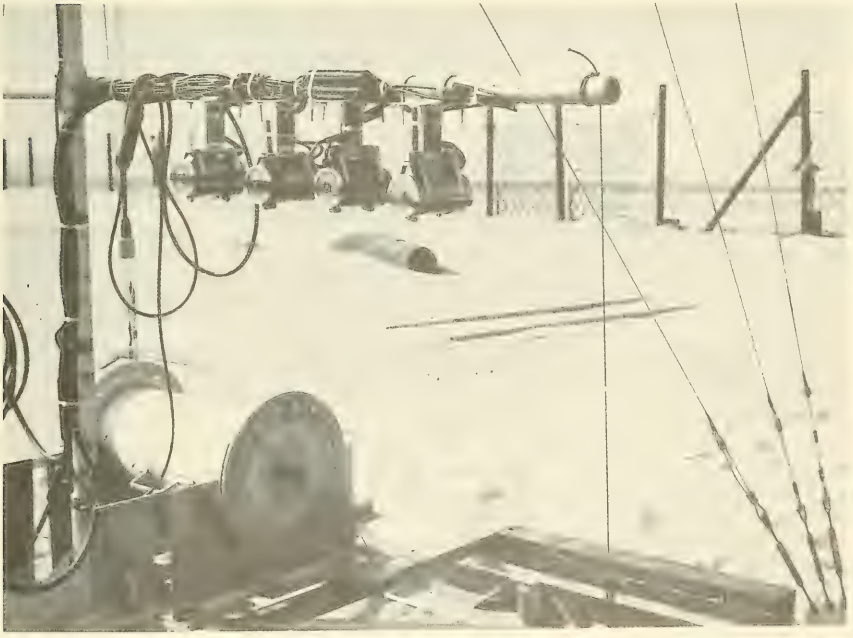


Figure 27. Field testing of current meters.

relate these to sediment properties and bed form types; and (c) to determine what the longshore current distributions are on both sides of the breaker zone. All of these relate to the need for understanding coastal sediment transport.

Several models have been proposed in the past for the distribution of longshore currents, the causes of current generation, and the resulting littoral drift. However, systematic studies for testing these models in the field have not been carried out, even for simple topographies, monochromatic waves, and unobstructed coastlines. Verification of the shore-normal distribution of longshore currents is important, the studies to begin under the simplest environmental conditions, progressing to include complex bathymetry, tides, and low-frequency components of general circulation, to application of the modified models to the design, evaluation, and maintenance of coastal structures.

Since numerical models of coastal currents are currently based on mean velocities, the vertical distribution of currents combined with their lateral variability is unknown. First-order importance in sediment transport studies is knowing the structure of the velocity field and being able to extrapolate profiles to the bottom, especially where entrainment is concerned as boundary layer development and the boundary where distribution governs the motion of sediments. Therefore, experiments must be designed to obtain current data near the bottom.

In surface current measurements it is necessary to keep a constant distance between the reference water level (mean lower low water (MLLW) where tides are present) and the point at which currents and waves are measured (Fig. 28a). If the nearshore slope is uniform, all sensors can be arranged to move downward only and parallel to the mast at constant increments. Although this operation is not difficult, it may require extended periods of underwater work to adjust spars and realine meters into the three coordinates during which the main features of the nearshore circulation system (wave, wind, and current directions) can change.

In the study of sediment entrainment, transport, bed form generation and maintenance, and bottom friction, the flow of water near the bottom must be measured (Fig. 28b). For this measurement (but not exclusively) at least three points of flow readings in the vertical are needed to define the velocity gradient and in turn imply the form of the boundary layer, and the distribution of boundary shear. This is a relatively straightforward procedure when operating on gentle, uniform slopes; however, both steep or barred offshore profiles can complicate the design of an experimental grid. The problem in data analysis of such a scheme is the evaluation of the variable pressure-response factor resulting from the continuously changing depth at the wave gage. Since equidistant or "equi-depth" spacing of the sled positions usually generates data gaps (Fig. 28c), it is more advantageous to survey the profiles beforehand and use the fathometer profile to determine positions for the sled; i.e., on bar crests, bar troughs, or midpoints on bar slopes where data will contain similarities

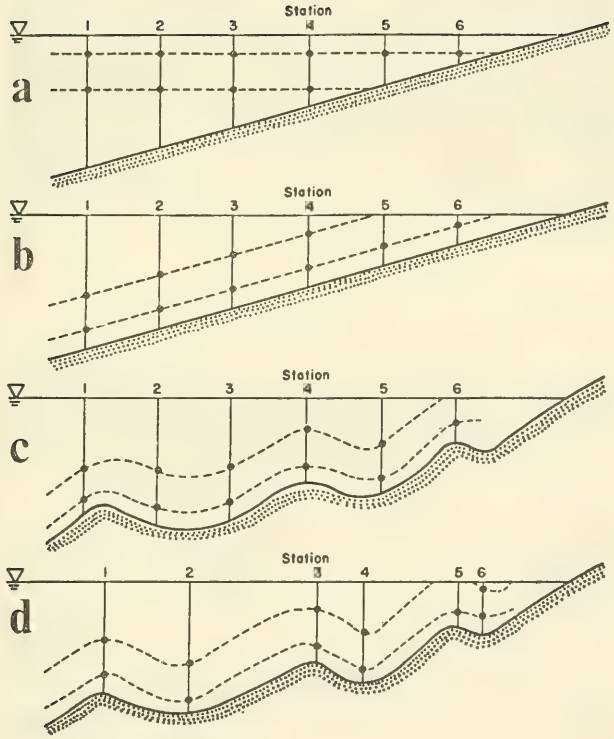


Figure 28. Experimental grid for sea sled experiments.

(Fig. 28d). For this control, a minimum of a pair of onshore navigation targets to sight on and a transit to read cutoff angles to the sled are required.

b. Sensor Configurations. The optimum design for measuring the distribution of coastal currents along a horizontal profile should consist of at least nine bidirectional ducted current meters, in groups of three, and alined orthogonally to one another (Fig. 29) at elevations near the surface, at middepth, and near the bottom. Each sensor measures the current speed concurrently along the three axes and from these data the mean vector can be resolved and velocity computed. Alternately, paired electromagnetic sensors may be used. Where vertical orbital velocities are negligible (shallow water or high-frequency waves), pairs of B-10 meters mounted horizontally at right angles have been used (Fig. 30); however, in the reconstruction of the vertical velocity profile, less than three points in the vertical are inadequate. The wave gage is best situated adjacent to the lowermost group of meters, thus assuring that pressure records will be collected even with the least number of submerged current meters.

c. Operations. Common to all these objectives is the incremental movement of the platform, usually commencing in deep water and ending where water depth becomes less than 0.91 meter. The reason for not carrying the measurements up to the dry beach is that the placement of sensors below the upper rim of the cylinders would introduce a bias into the records. The actual operation requires towing the sled to 9.14 meters offshore, where the first record is usually obtained, followed by its consecutive shoreward displacement to a predetermined location or predetermined water depth. In most operations the sled needs to be decoupled from the towing vessel, especially in heavy swell.

Minimum personnel required for continuous surveys where sensors are used in fixed position throughout the experiment, include a LARC operator, a deckhand to release the sled cables, a transit operator, and a data station operator. However, standby divers must be available for emergency underwater work; when surface currents are measured the divers are used to readjust spars on the sled each time the water depth has changed.

d. Data Collection. Several data recording options may be exercised with each experiment (Table 3). A data file convenient to analyze should consist of less than 2^{12} words per sensor. Usually 5 to 7 minutes of recordings per station along the shore-normal profile are adequate for analyzing that part of the record which contains the wave-induced currents. Since the principal aim of such a study is to observe the spatial actions without a change in the local wave, current, and wind climates with longer recording times, the uniformity of conditions during the measurement period may be foresaken. An example of the mean longshore velocities along a profile is shown in Figure 31. The time-series analysis which includes Fast Fourier Transform (FFT) programing is also used to calculate the energy spectra for each sensor (Fig. 32).

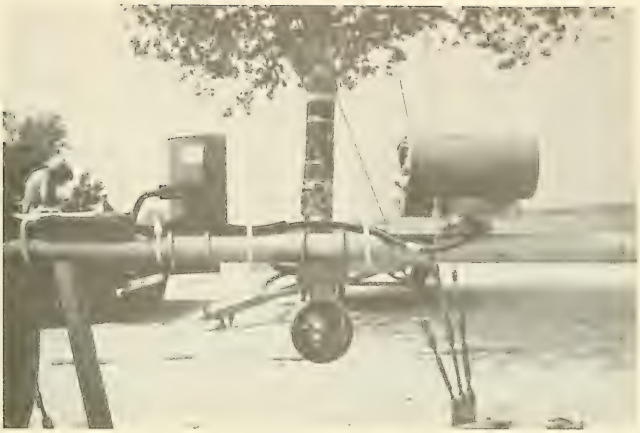


Figure 29. Orthogonally mounted current meters.

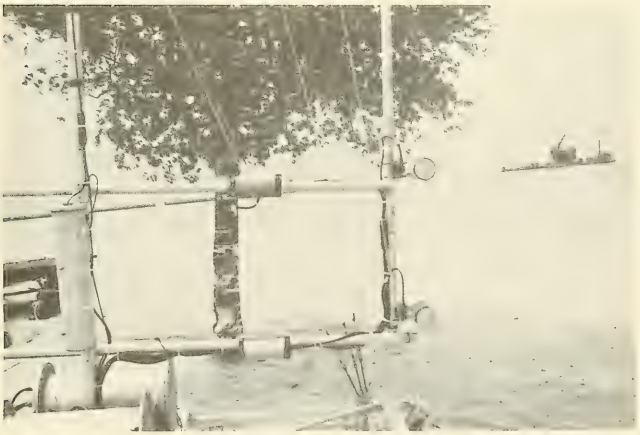


Figure 30. Pairs of horizontally mounted current meters.

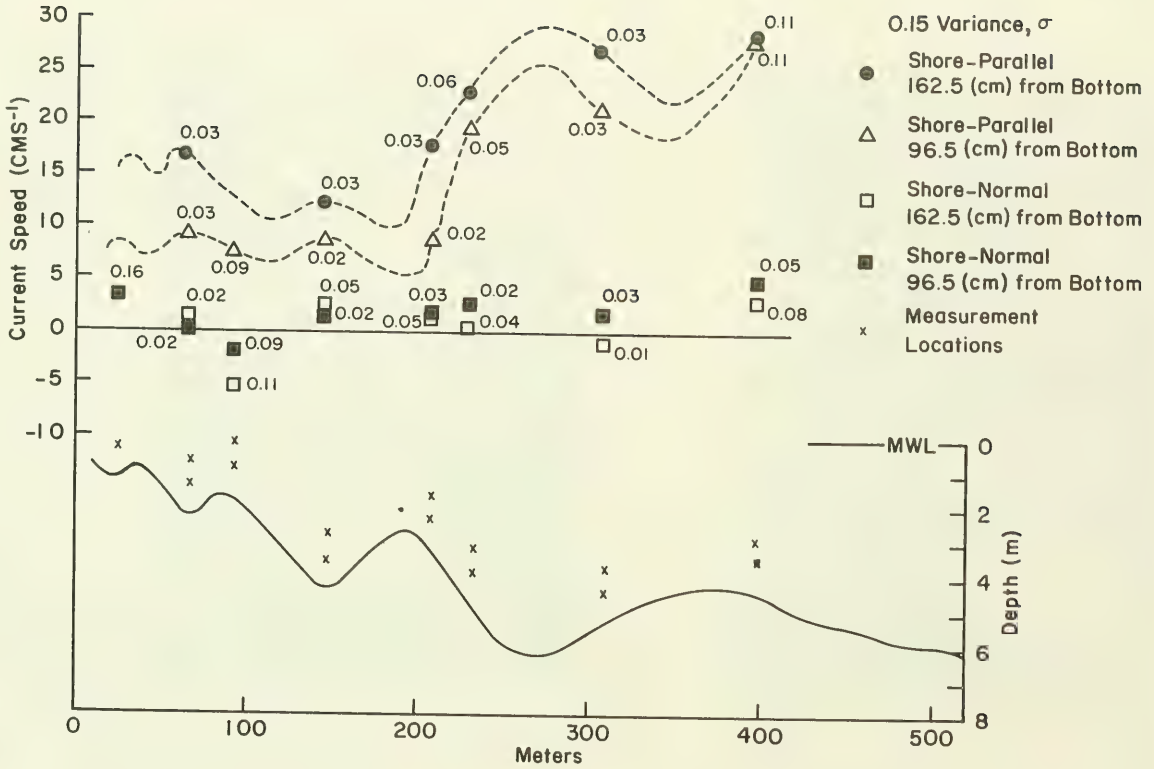


Figure 31. Example of longshore current distribution over a barred offshore profile (Teleki, Schwartz, and Musialowski, 1976).

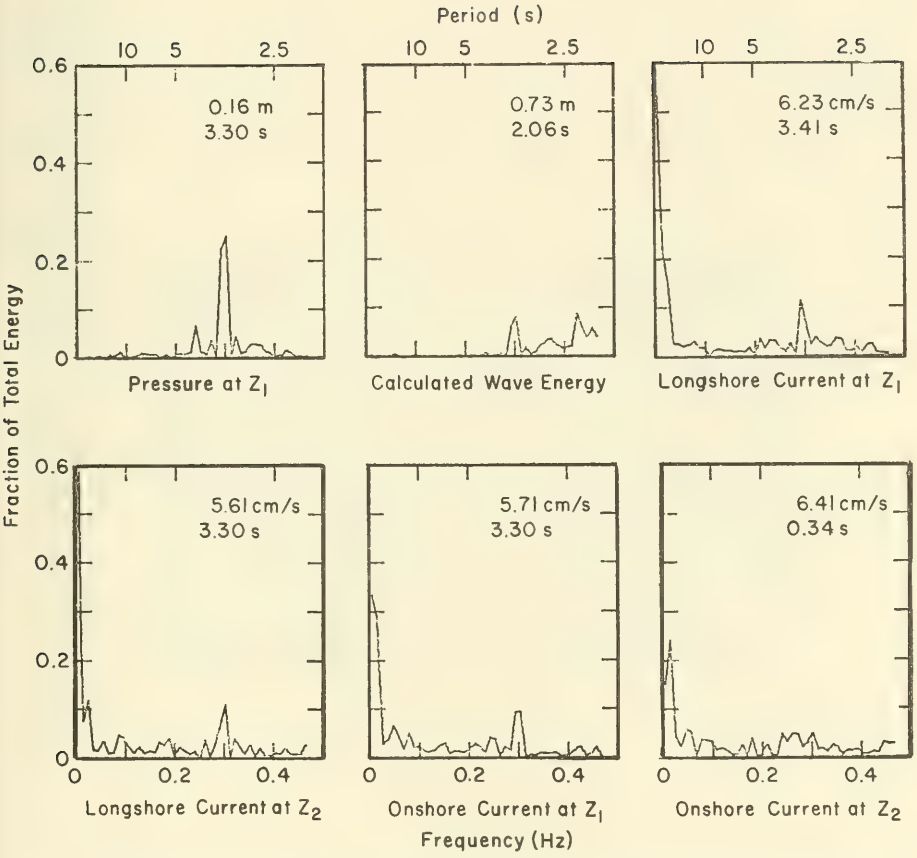


Figure 32. Example of energy spectra along shore-normal profile (Teleki, Schwartz, and Musialowski, 1976).

2. Fixed-Point Measurements.

a. Rationale and Needs. At times it is desirable to obtain a time-series record of flow at a given point to (a) assess the contribution of slowly varying ocean parameters, such as connected to tides and seiches, and (b) record the wave and the directional current spectrum with changing barometric pressure, wind velocity, and direction at a particular site of interest. In this case deployment of current meters in the vertical is preferred to allow measurement of the propagation of long waves through time and to determine attenuation with depth.

b. Sensor Configurations. The manner in which sensors are deployed during *in situ* measurements is a variation of designs discussed previously. The configuration chosen was either an equidistant placement of four sensors in the vertical, alined parallel to shore (Fig. 33), or three deployed in the same manner with the fourth oriented shore-normal adjacent to the wave gage. The latter design assures that some record of the incident wave orbital velocities is collected while the velocities in the vertical profile are also recorded.

c. Data Collection. In 260 hours (10.83 days) of continuous recording by the system onboard the sea sled, long time-series records can be obtained with TODAS at any site, even if remotely located. This capability can be extended to 65 days if data were to be collected once every hour for 10-minute periods. Because the batteries are regenerative, 80 to 90 days of operation may be feasible in this manner.

3. Fixed-Point Measurements Combined With Lagrangian Techniques.

The measurement of flow at a fixed point is regarded as the Eulerian technique of measurement. The technique is a record of events passing through the fixed point, and these events can be related to the Lagrangian velocity by:

$$V_i(a,t) = u_i\ (X(a,t),t) \quad ,$$

where u_i is the Eulerian velocity measured at the fixed probe, t is time, $X_i(a,0) = a_i$ is the Lagrangian position, and V_i is the Lagrangian velocity.

The Lagrangian position of a moving fluid particle in space is:

$$X_i\ (a,t) = a_i + \int_0^t V_i\ (a,t')dt' \quad ,$$

and the measurement of V_i requires tagging the particle so that it can be followed and recorded in the interval t-t'. Because the statistics of u_i are not related to V_i in a simple way (Tennekes and Lumley, 1972), it is best to record them simultaneously to evaluate both the time-dependency and space-dependency of the moving fluid in the experimental area.

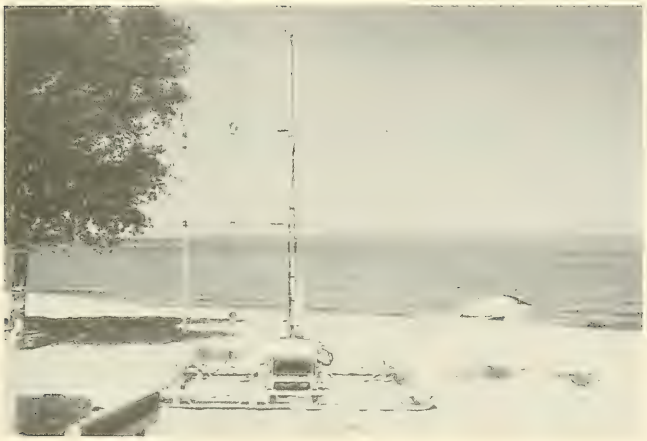


Figure 33. Current meters alined for measurement in vertical profile.

For Lagrangian measurements, several techniques have been developed, tested, and used. Methods included are the use of dyes, or floats, drogues, cards, confetti, and other free-floating objects. While drogues are designed to eliminate measurement of all but the mean fluid motion, dyes on the opposite end of the scale respond to microfluctuations in the movement of water masses, and thus are true tracers of water particles themselves. However, their use requires evaluation of both the advective motion and the diffusive and dispersive properties of water masses.

a. Rationale and Need. Dyes have been used as tracers of the quantity V_i, probably because of the difficulties experienced in designing drogues which readily responded to wind drag and wave motion. Although some of the reasoning for this and some of the techniques have been reported in Teleki, White, and Prins (1973) and Teleki and Prins (1973), it is best to enumerate the conceptual model required to carry out combined Eulerian-Lagrangian experiments.

Nearshore waters are generally turbulent which means considerable mixing (momentum exchange) is taking place throughout the water column. In this environment, simple measurement of the flow with a fixed probe cannot provide an estimate of the eddy diffusion coefficient, E_i, which is the measure of dispersion of mass resulting from the turbulent velocity fluctuations and can be written as:

$$E_i \frac{\partial C_i}{\partial x'} = \overline{V_i' C_i'} \text{ for } (i = x, y, z) \quad ;$$

E_i is related to the dispersion coefficient in:

$$E_i \frac{\partial C_i}{\partial i} = \overline{u_i'' c_i''} + (k_i + c_i) \frac{\partial C}{\partial i} \quad ,$$

where $C_i = \overline{C}_i - C_i''$ is the deviation of the concentration of a conservative tracer from the mean, $U_i = \overline{u}_i - u_i''$ is the deviation of the velocity from the mean, k_i is the molecular diffusion coefficient, and E_i is the diffusion coefficient. The Eulerian velocity, u_i, is used in the above expression because its statistics are better known than that of V_i.

Fixed-probe measurements provide an easier solution of a given algorithm than a probe moving with the velocity V_i, because the techniques developed for the statistical manipulation of time-series data are well understood, e.g., compared to the Lagrangian integral scale in which such quantities as the mixing length and dissipation rate are needed but are difficult to estimate.

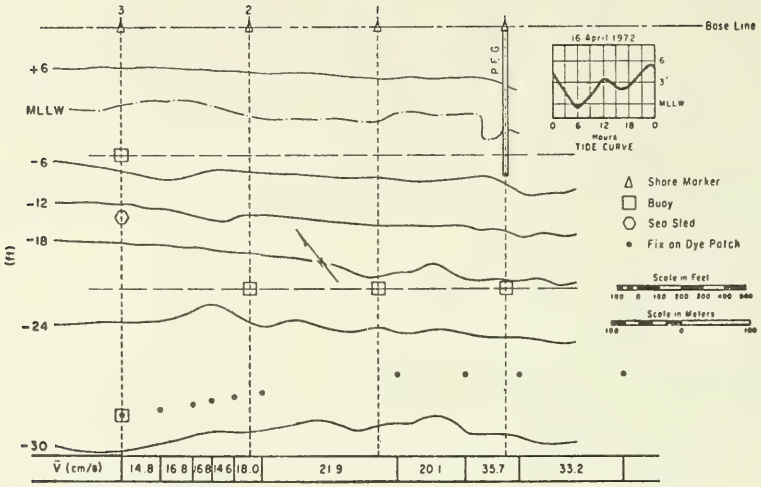
Near the coast and especially near engineering works, there may be an interest in what is referred to as "general circulation." This is a series of synoptic snapshots of currents past an object designed to train, divert, or obstruct the same flow, or the sediment it carries. The engineer is asked to evaluate the performance of the structure for which he needs to know what the areal variations in waves and currents are. Measurement of velocities in the Lagrangian domain is an answer. Unfortunately, present techniques are designed for surface measurements only and not for the flow

near the bottom boundary. To overcome these limitations, experiments were conducted to combine the surface tracing of dyed waters with the velocity measurements in the vertical profile at a stationary point. The purpose is to correlate V_i and u_i, corresponding to the dye velocity and the velocity measured by metering, respectively, and requires that the sled-mounted meters be positioned in the field where the dye is dispersing. Correlations can only be carried out in the area immediate to the fixed-point sensors, irrespective of the type of dye injection used (Fig. 34). However, this method can be improved by spacing two sets of current meters at the upstream and downstream boundaries of the area where dyes are traced, correlate the Eulerian velocity scales for the Lagrangian domain, then use the results as a check on the dispersion and diffusion of dye through the control area.

Dye releases require preselecting the algorithm which will later govern the analytical procedures. Three injection techniques will satisfy this: (a) Continuous injection at a point, (b) continuous line injection, and (c) point source (slug) injection. Choice of injection is influenced by geographical, physical, or operational constraints and whether the experiment is designed to study convective properties of the flow.

Continuous injection requires flow conditions in the control (measurement) area to be homogeneous. The technique is based on the principle of "steady dilution," i.e., the tracer concentration stabilizes in time as its properties become representative of the flow properties themselves. Steady dilution requires a complete mixing over time-length of the system and a single sample from the well-mixed (equilibrium) condition. The disadvantage of this algorithm for use in coastal areas where the time scales associated with molecular diffusion, advection, and turbulent diffusion vary in space and time, is that the additional requirements of steady, unidirectional flow and high discharge rates cannot be met; thus, the mixing length cannot be estimated. Use of a line injection will not materially alter the analytical problems experienced with point injections. However, this technique is useful for charting flow lines near coastal engineering works because the variability in surface flow velocities, the mixing zone, and the pulsating and meandering nature of coastal currents can be observed.

If a single-point injection is used, time integration may be applied. The drawbacks associated with the algorithm are that complete lateral mixing and high-discharge steady flow are still required, and the dye field must be sampled continuously at a fixed point and fixed depth for the estimation of the mixing length. This method is best applied to tidal inlet flow studies where the physical boundaries present and the quasi-steady, high-discharge tidal flows staisfy the minimum requirements. Another algorithm built around single-point injections is the spatial-integration technique where the center of gravity of a diffusing-advecting cloud is found and the concentration is measured. If the instantaneous position of the centroid is denoted by $x_i(t_o)$, the difference $x_i(t_o) - x_i(t_o)$ becomes a measure of V_i. Therefore, it is critical to know the depth to which the tracer cloud has diffused at each position and



Time (h-s)	Dye transport (cm/s)	Average current speed (cm/s)			
		4.57	3.43	2.29	1.14
			above bottom (m)		
14:37 - 14:40.5	14.8	26.28	18.71	19.01	14.81
- 14:45	16.8	23.35	18.41	18.09	12.17
- 14:48	16.8	24.63	20.90	18.13	13.32
- 14:51.5	14.6	27.77	21.9	20.65	16.19
- 14:55	18.0	24.50	19.69	23.04	16.33
- 15:10	21.9	28.50	22.44	26.20	20.16
- 15:18	20.1	30.78	25.68	17.28	12.11
- 15:21.5	35.7	29.08	25.97	15.69	10.85
- 15:29	33.2	24.15	23.58	20.48	14.63

Figure 34. Comparison of velocities from dye transport and current meters.

instance corresponding to each $x_i(t)$. After the concentration contours are derived, the evaluation of the eddy diffusivity coefficients, ε_i, is simplified.

b. Selection and Use of Dye Tracers. Water-tracing dyes must be chosen according to whether their colorimetric or fluorometric properties are to be measured or imaged. Generally, the emissivity of fluorescent substances (measured in milliwatt per square centimeter steradians) is much higher than nonfluorescing chemicals and the bandwidth of transmittance is usually narrower, all of which aid the spectral separation of one tracer from another. In tests at Oceanside and Point Mugu, California, and at Pentwater, Michigan, three dyestuffs in green, yellow, and red bands of the visible spectrum were commonly used (Table 4). These substances have been used in pollution research and rescue operations; none is toxic to living organisms.

c. Dye Injection Procedures. Dyes are normally injected by placing 100 grams of the material in a water-soluble film or bag, which in turn is placed in a porous sand-sample bag. The inner container retards solution of the dye until the film dissolves; the porous sand-sample bag allows the solution to pass through and keep the dye fixed in position. Six bags are usually attached to an anchored buoy line and positioned 0.3048 meter (1 foot) below the water's surface. This method does not satisfy any of the injection schemes discussed previously since the dye release is neither instantaneous nor at a constant discharge; however, this type of injection is useful in aerial photography of nearshore circulation. Where the spatial integration method is used, the dye packets are tied to a free-floating buoy which marks the advective path, and the surrounding developing dye patch will indicate the rate of diffusion outward from the source. In steady dilution, a pump must be used to inject the tracer at a known discharge rate.

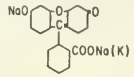
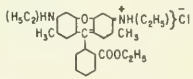
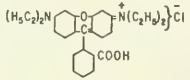
A typical experiment involves designing a control grid to locate the centroid or leading edge of the dye; e.g., where a combination of six buoys and six shore targets were used to provide sufficient control to (a) determine the position of the cloud, and (b) rectify oblique images to vertical equivalents (Fig. 35).

Although drogues and floats are used in nearshore experiments for the charting of currents, their physical size is not representative of a volume of water small enough to have the scales of molecular diffusion. Wind stress on the surface also tends to modify their path to the extent of overriding the advective properties of the fluid. Where offshore bathymetry is undulating (bars, shoals), these objects often ground for short periods. Therefore, correctly traced dye clouds will better depict the true course of nearshore currents.

4. Aerial Photography.

a. Survey Flight Lines and Frequency of Coverage. To piece together the distribution of currents both in the lateral (y-coordinate) and the

Table 4. Properties of water-tracing dyes.

Generic name	Alternate name		Color index no.	Chemical composition	Spectra (expressed in nanometers)		Color of fluorescence
	By substitution	By solubility			Absorption (max)	Emission (max)	
Uranine B	Na-fluorescein	Acid yellow 73	45350		493	518	Greenish yellow
Rhodamine 6GDN	Brilliant pink 5G Rhodyle 4G Rosazein 6G Safranolin 5G Trianisoline	Basic red 1	45160		530	565	Yellowish red
Rhodamine B	Tropaeolin O, Rhodamine B Base -B extra, -NB, -EB, -O; Brilliant pink B Carthamine B Fat red A Rosazein A Safranolin	Basic violet 10	45170		550	605	Red

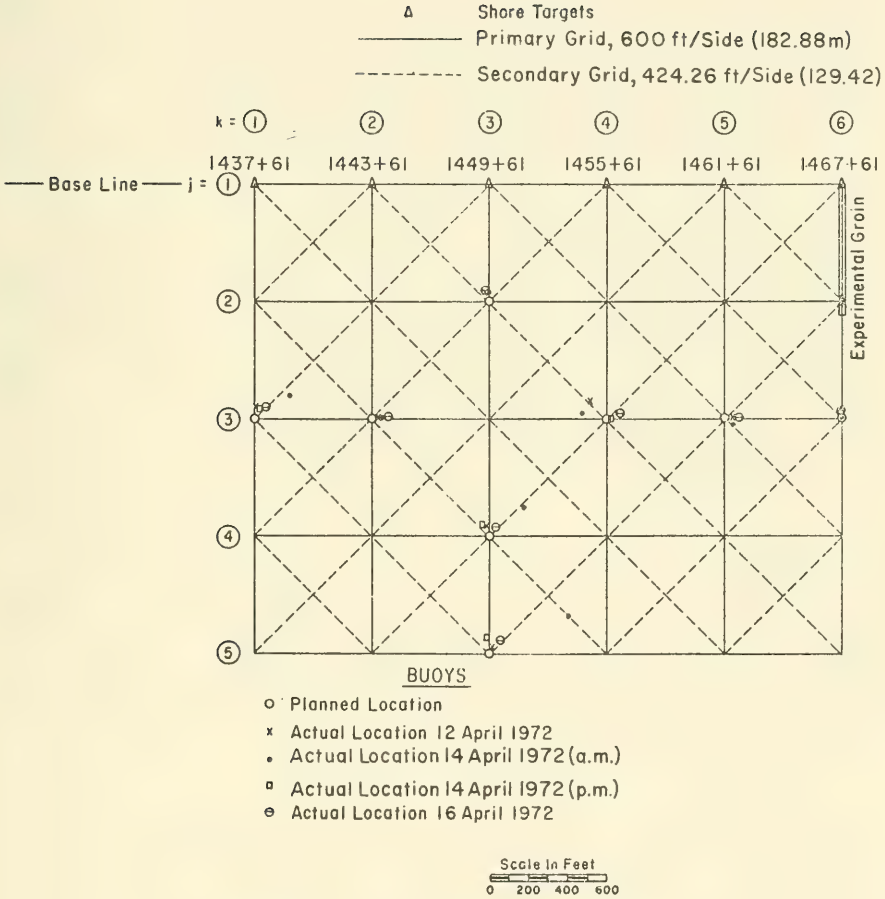


Figure 35. Buoy shore-marker grid.

longitudinal (x-coordinate), the position of the dyed water mass must be recorded from the time of injection to time t_n, where n signifies the limit of control area delineated by the grid. Photo coverage in time increments is a first-order necessity for this purpose. The flight lines for an area of 1,280.16 meters square (4,200 feet) can vary from a single pass at 2,316.48 meters (7,600 feet) to multiple passes at lower altitudes. Given a cluster of 70-millimeter cameras with 100-millimeter focal lengths, the typical field of view for 1,066.8 meters (3,500 feet) (flight altitude) is 591.62 meters square (1,941 feet) (a photo scale of 1:10,672), typically with 30-percent sidelap and 50-percent endlap (Fig. 36). Experience indicates that 2 to 2.5 hours flight time is required for an area of this size to complete advection of the 600 grams of dye used per injection point, resulting in about 80 to 90 frames exposed per camera.

b. Multispectral Photography. Aerial films should be exposed for water, rather than land. The product can be considerably enhanced by selecting the films in combination with filters responding to the bandwidth at which either the fluorometric or colorimetric reflectance of the dyes in the field is at maximum. Several film-filter combinations can be selected in this manner, preferably one for each tracer and without spectral overlap. The resulting system becomes multispectral (whether black and white or color films are selected for each bandwidth) and the extended dynamic range thus allows certain processing techniques to be applied and analytical methods (color recontruction; density slicing) to be practiced for the evaluation of the image content.

If vertical photos are difficult to obtain, oblique photos can be used by rectifying the images with the aid of an instrument such as the Zoom Transfer Scope (Bausch and Lomb) (Fig. 37). The scope functions as a *camera lucida*, i.e., the superposition of two images, two maps or an image and a map through an optical system becomes possible. Rotation, stretching and zoom capabilities of the scope allow the user to match control points, scales, and within limits rectify the obliquity in an image for the vertical resolution or vice versa. This instrument is useful in the collation of information from imagery of varying scales onto a common engineering map. Use of oblique photos in dispersing dye and the reduced information are shown in Figure 38.

Data to be extracted from photos include the measure of V_i, the advective property of the dye plume. V_i can be estimated from the propagation of the leading edge of the plume with time; however, it is not indicative of the true transport of mass. To obtain the correct estimate, the center of the propagated mass must be determined and its displacement traced with elapsed time; e.g., methods used include: (a) The sampling of dye patch from boats or with automatic samplers at various geographic points and in time (Kilpatrick and Cummings, 1972); (b) the measurement of the tracer concentration with a aerial Fraunhofer camera or Fraunhofer line discriminator (Hemphill and Stoertz, 1969); and (c) the analytical processing of imagery which includes density slicing.

Although the last method is strictly qualitative, it can be quantized with controlled sampling of the water mass during the course of photographic flights.

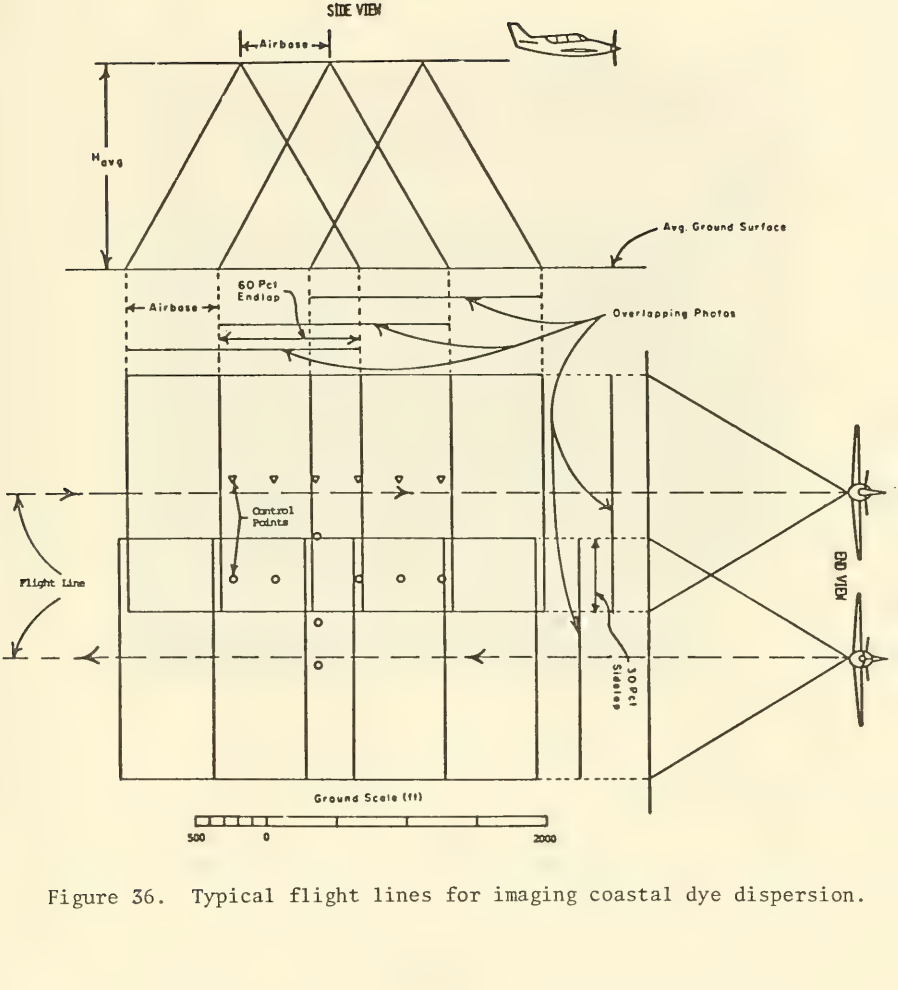


Figure 36. Typical flight lines for imaging coastal dye dispersion.

Figure 37. Zoom Transfer Scope.

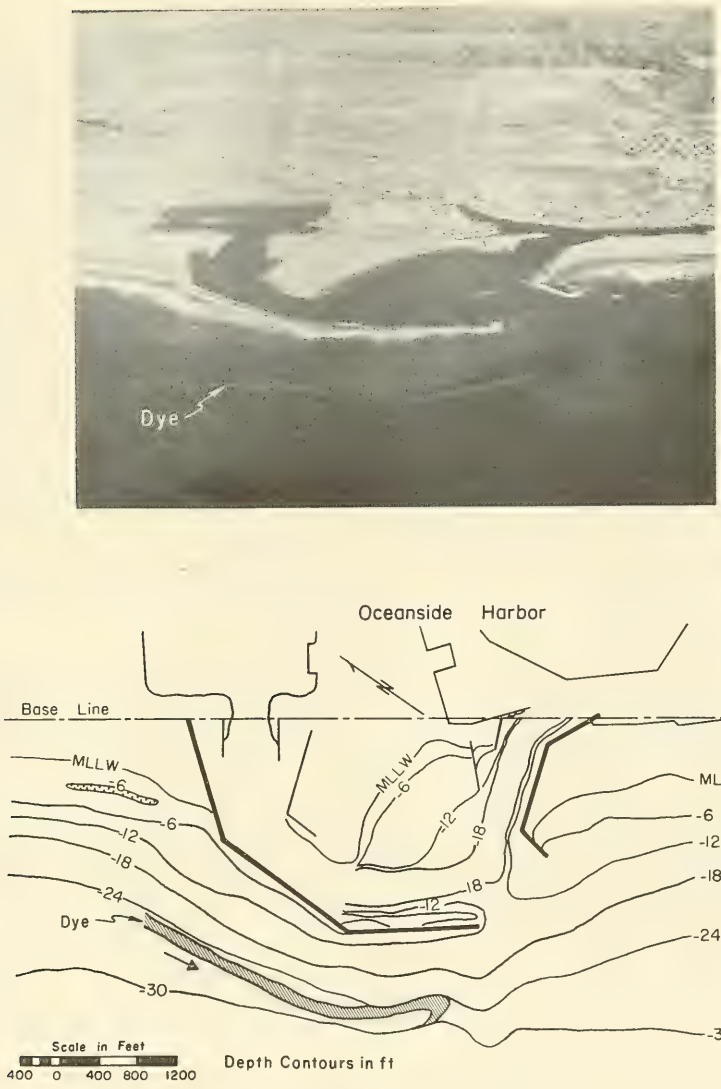


Figure 38. Oblique photo of dispersing dye and map of rectified photo.

V. CONCLUSIONS AND RECOMMENDATIONS

Techniques related to the measurement of flow in the nearshore zone have been surveyed, and the advantages and disadvantages associated with the various approaches discussed. The advantages are: (a) The ability to negotiate the surf zone with instruments mounted on the sea sled; (b) a near-continuous mode of operation for measuring waves and currents contemporaneously and chart their distribution in the spatial sense; (c) to see the data in real time for maximizing the conditions in collecting useful information; and (d) the ability to combine Eulerian and Lagrangian techniques for the complete description of flow.

The disadvantages are: (a) The present inability to obtain Lagrangian correlation scales independent of dye studies by measuring currents simultaneously with sets of meters at two locations; this requires another sea sled and corresponding instrumentation for the two platforms to be deployed at the upstream and downstream boundaries of the test area where diffusion studies are conducted; (b) the time needed to adjust the spars so that data points in space would be dispersed equidistantly from one another and from the reference water surface, thus providing a means to record wave attenuation along a shore-normal profile using a constant pressure correction factor; and (c) the present method of measuring currents near the bottom boundary. The location of the instrument and powerpacks restricts mounting of sensors to elevations 0.91 meter above the bottom, when placements closer to the ocean floor may penetrate the boundary layer of slowly varying shelf currents.

The sea sled is an ideal vehicle for the measurement of currents and waves (as presently done), or salinity, temperature, and sediment content. Water temperatures were read during one of the experiments, including windspeed and direction necessary to estimate the influence of wind stress on the time required to set a lake into motion or on the dispersal of a dye plume.

The dye experiments are an integral part of a nearshore current study, because mixing (turbulent diffusion) is nonnegligible near the coast and the records obtained from *in situ* sensors contain information on the turbulent part of the spectrum. The development of a dye plume is followed by aerial cameras which record the zones of intense mixing, allow the experiments to assess the aerial variations in current speed at the surface near the fixed-point sensors, and thus gain insight of upstream histories for the coastal flow. Repetitive photo coverage is useful in estimating horizontal and lateral diffusion coefficients when the proper injection algorithm is applied and the dye concentrations are measured in the field.

The ultimate use of such information is for sediment transport calculations in coastal areas and for the evaluation of the performance of engineering structures. Necessarily, these are often interrelated. However, a sufficiently wide range of environmental conditions may be tested in time, the evaluation of which would result in producing predictive models and design curves useful to the coastal engineer. This study has documented these needs and expectations, provided an insight into the problems, and recorded some of the accomplishments.

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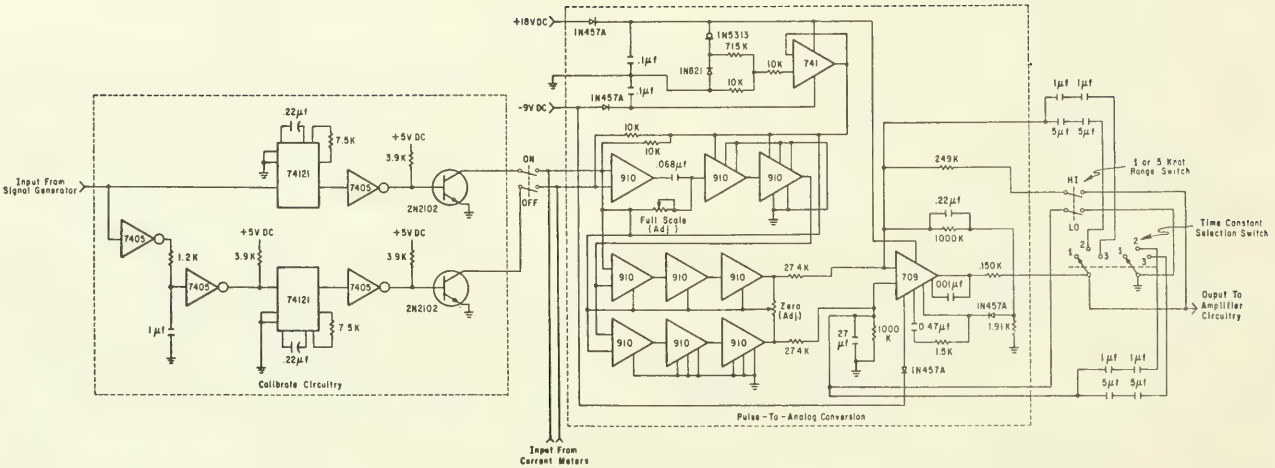
APPENDIX

Schematics of onboard electronics; letters refer to generalized chematic in Figure 16.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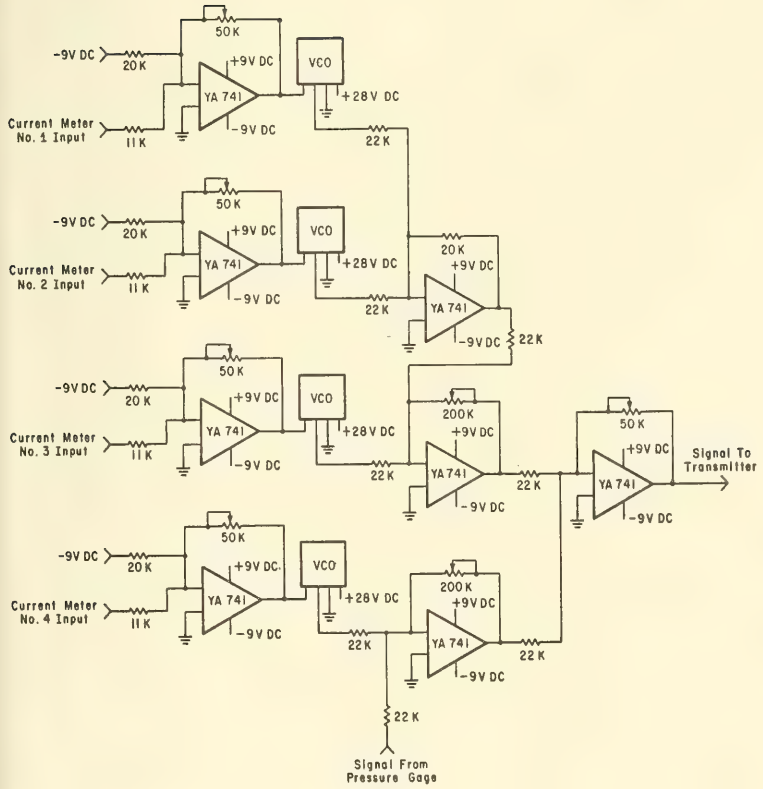
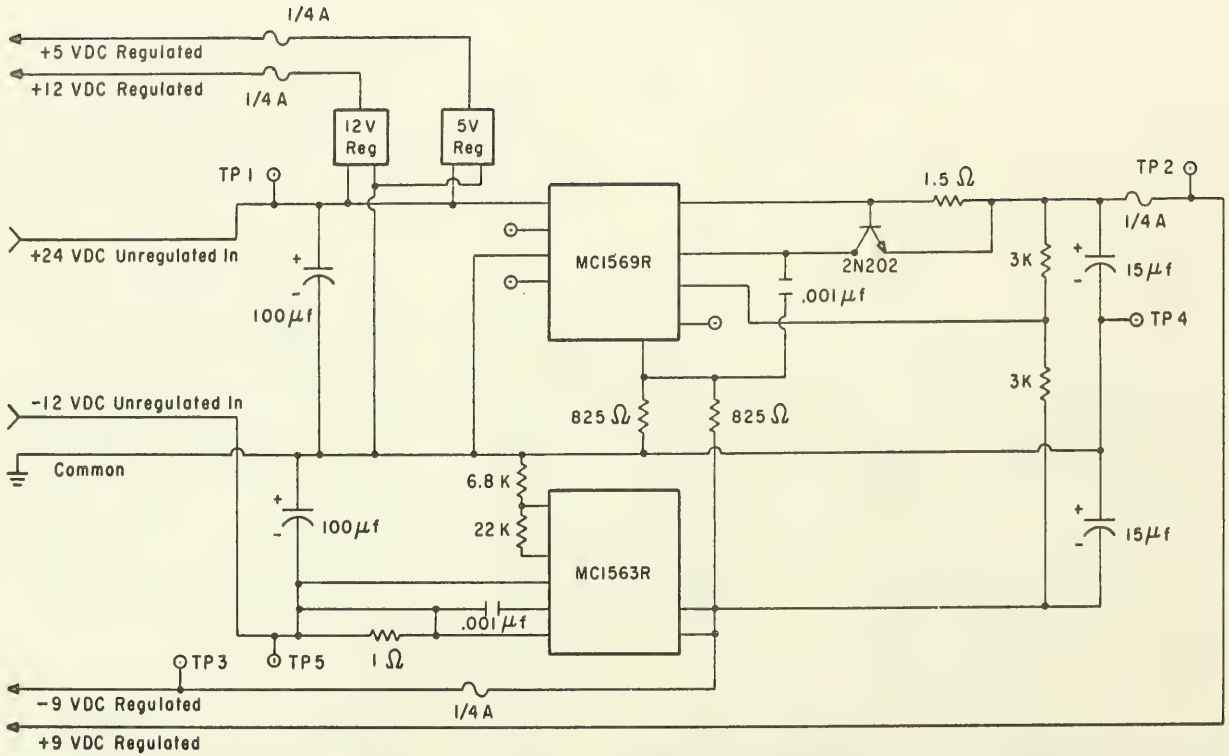
74121
7.5K
+5V DC
3.9K
7405
2N2102
1.2K
1μf
Calibrate Circuitry
+18V DC
-9V DC
IN457A
.1μf
IN5313
715K
IN821
10K
741
910
.068μf
Full Scale (Adj.)
ON
OFF
Input From Current Meters
249K
.22μf
1000K
HI
LO
1 or 5 Knot Range Switch
Time Constant Selection Switch
Ouput To Amplifier Circuitry
27.4K
Zero (Adj.)
709
.001μf
.150K
1000K
0.47μf
1.5K
1.91K
27μf
1μf 1μf
5μf 5μf
Pulse-To-Analog Conversion

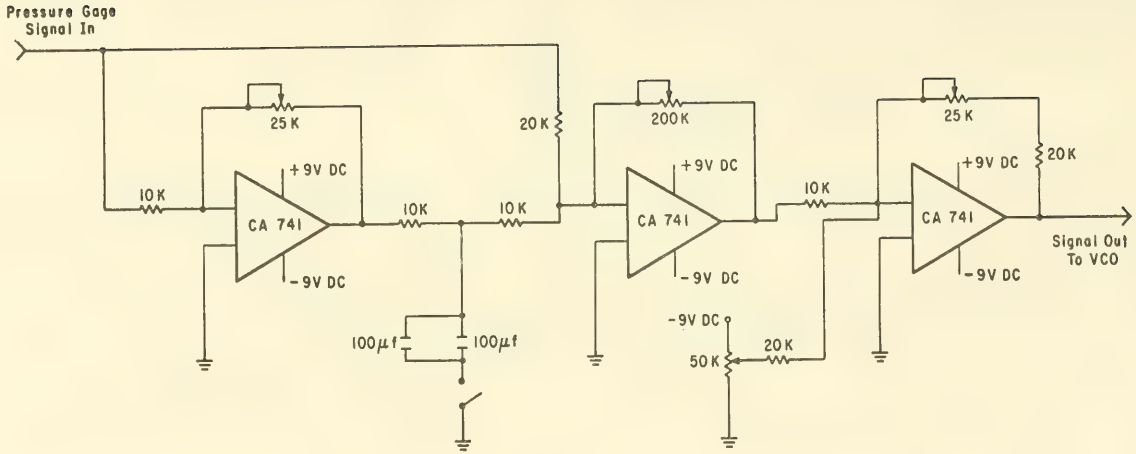
A


-9V DC
20K
50K
+9V DC
YA 741
-9V DC
VCO
+28V DC
Current Meter
No. 1 Input
11K
22K
-9V DC
20K
50K
+9V DC
YA 741
-9V DC
VCO
+28V DC
Current Meter
No. 2 Input
11K
22K
20K
+9V DC
YA 741
-9V DC
22K
-9V DC
20K
50K
+9V DC
YA 741
-9V DC
VCO
+28V DC
Current Meter
No. 3 Input
11K
22K
200K
+9V DC
YA 741
-9V DC
22K
50K
+9V DC
YA 741
-9V DC
Signal To
Transmitter
-9V DC
20K
50K
+9V DC
YA 741
-9V DC
VCO
+28V DC
Current Meter
No. 4 Input
11K
22K
200K
+9V DC
YA 741
-9V DC
22K
22K
Signal From
Pressure Gage

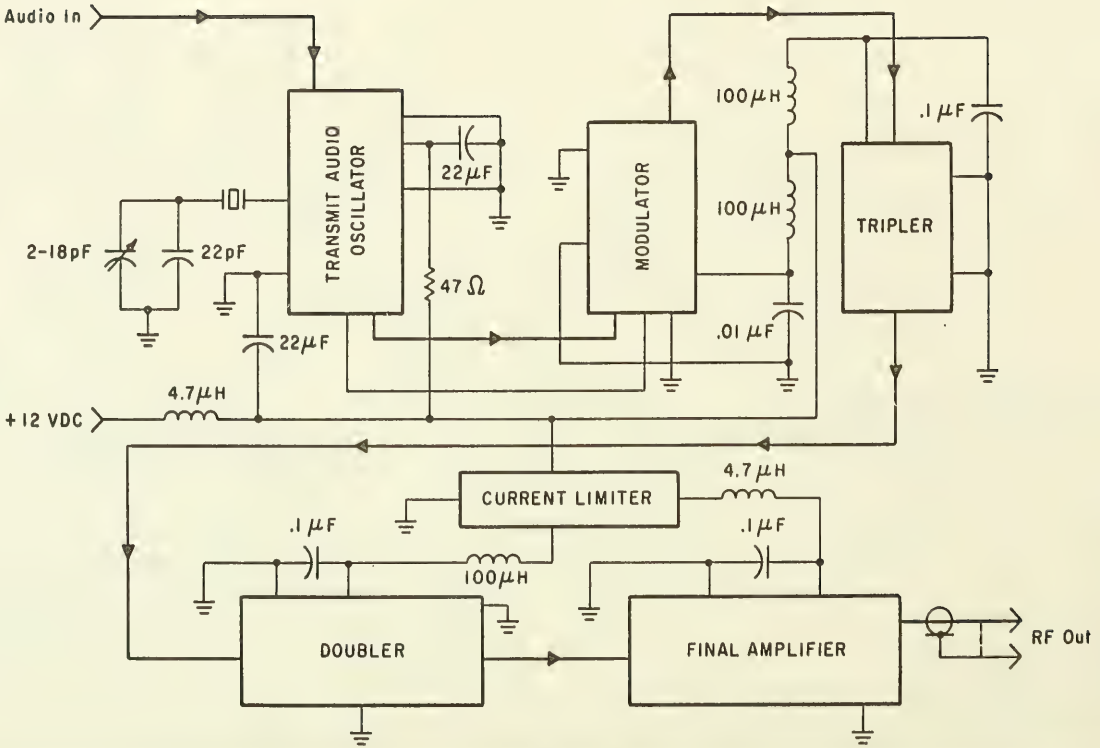
B


1/4 A
+5 VDC Regulated
+12 VDC Regulated
1/4 A
12V Reg
5V Reg
TP 1
+24 VDC Unregulated In
100μf
MC1569R
1.5 Ω
2N202
.001μf
3K
15μf
TP 2
1/4 A
TP 4
3K
-12 VDC Unregulated In
825 Ω
825 Ω
Common
6.8 K
22 K
100μf
MC1563R
15μf
.001μf
1 Ω
TP3
TP5
-9 VDC Regulated
1/4 A
+9 VDC Regulated

C


Pressure Gage
Signal In
25 K
20 K
200 K
25 K
+9V DC
+9V DC
+9V DC
20 K
10 K
CA 741
CA 741
CA 741
10 K
10 K
10 K
-9V DC
-9V DC
-9V DC
Signal Out
To VCO
100μf
100μf
-9V DC
50 K
20 K

D


Audio In
TRANSMIT AUDIO OSCILLATOR
22μF
2-18pF
22pF
47Ω
22μF
4.7μH
+12 VDC
MODULATOR
100μH
100μH
.01μF
TRIPLER
.1μF
CURRENT LIMITER
4.7μH
.1μF
.1μF
100μH
DOUBLER
FINAL AMPLIFIER
RF Out

Teleki, P.G.
Measurement techniques for coastal waves and currents / by P.G. Teleki, F.R. Musialowski...[et al.]. – Fort Bevloir, Va. : U.S. Coastal Engineering Research Center, 1976.
75 p. : ill. (Miscellaneous report – Coastal Engineering Research Center ; 76-11)
Bibliography : p. 69.
Report discusses a mobile battery-operated system (TODAS) consisting of a towed platform (sea sled) with current meters and a wave gage, developed for collection of data on nearshore currents and waves. TODAS can be used for real-time evaluation of flow characteristics between shore and a depth of 9.14 meters.

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TC203 .U581mr no. 76-11 627 .U581mr

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